

Effects of plyometric training on measures of physical fitness in racket sport athletes: a systematic review and meta-analysis

Nuannuan Deng¹, Kim Geok Soh¹, Borhannudin Abdullah¹ and Dandan Huang²

¹ Faculty of Educational Studies, Universiti Putra Malaysia, Selangor, Malaysia

² College of Physical Education, Chongqing University, Chongqing, China

ABSTRACT

Background: Over the past decade, the popularity of racket sports has surged. Plyometric training (PT) has been the focus of extensive research because of the proven benefits it provides to athletes. However, there is a lack of systematic reviews and meta-analyses specifically evaluating the impact of PT on physical fitness metrics in racket sport athletes. This study aimed to conduct a comprehensive review and analysis of evidence derived from randomized controlled trials (RCTs) to evaluate the effects of PT on measures of physical fitness among racket sports athletes.

Methods: The electronic databases PubMed, Web of Science, SCOPUS, and SPORTDiscus were systematically searched up to June 2023 without placing any restrictions on the publication dates. The PICOS method was adopted to establish the inclusion criteria: (a) healthy athletes who participate in racket sports; (b) a PT program; (c) a control group; (d) assessment of physical fitness components pre- and post-PT; and (e) RCTs. The records' methodological quality was assessed utilizing the Physiotherapy Evidence Database (PEDro) scale. The certainty in the evidence related to each outcome was evaluated using the Grading of Recommendations Assessment, Development, and Evaluation (GRADE) assessment. A random-effects model was used to calculate effect sizes (ES; Hedges' *g*) between experimental and control groups.

Results: There were 14 eligible studies of moderate-to-high-quality, involving 746 athletes in total. The results revealed small-to-moderate effects ($p < 0.05$) of PT on muscle power (ES = 0.46), muscle strength (ES = 0.50), sprint speed (ES = 0.45), change of direction ability (ES = 0.76), and reaction time (ES = 0.67), while no clear evidence was found on balance and flexibility. The training-induced changes in muscle power showed no significant difference ($p > 0.05$) between youth (ES = 0.72) and adults (ES = 0.40). There were also similar muscle power improvements (ES = 0.36–0.54 vs 0.38–0.56, all $p > 0.05$) for a length of ≤ 7 weeks with ≤ 14 total PT sessions vs > 7 weeks with > 14 total PT sessions, and ≤ 2 weekly sessions vs > 2 sessions. No adverse effects were reported in the included studies regarding the PT intervention. The certainty of evidence varied from very low to moderate.

Conclusions: Our findings demonstrated that PT has positive effects on important indices of physical fitness among athletes participating in racket sports. Future studies are required to clarify the optimal doses and examine interactions among training variables to further promote the physical fitness of this specific population.

Submitted 28 July 2023

Accepted 19 November 2023

Published 15 December 2023

Corresponding authors

Nuannuan Deng,

dengnuannuan117@gmail.com

Kim Geok Soh, kims@upm.edu.my

Academic editor

Vanessa Yingling

Additional Information and
Declarations can be found on
page 20

DOI 10.7717/peerj.16638

© Copyright

2023 Deng et al.

Distributed under

Creative Commons CC-BY 4.0

OPEN ACCESS

Subjects Kinesiology, Sports Medicine

Keywords Plyometric exercise, Power, Strength, Sprint speed, Agility, Reaction time

INTRODUCTION

Racket sports have gained worldwide popularity and continue to grow in prominence (*Wörner & Safran, 2021*). The major racket sports include badminton, racquetball, padel, tennis, table tennis, and squash (*Cádiz Gallardo et al., 2023*). In these games, players utilize a handheld racket to propel a projectile back and forth, aiming to strategically position it in a way that prevents their opponent from successfully returning it (*Lees, 2003*). Moreover, these games involve a defined playing area in which the projectile must remain and a certain obstacle that it must surpass during each exchange (*Lees, 2003*). Success in racket sports heavily relies on both aerobic and anaerobic capacity, as players need a combination of quick reflexes, anticipation, change of direction ability, speed, and flexibility to swiftly reach the ball and avoid errors (*Fernandez, Mendez-Villanueva & Pluim, 2006; Edel et al., 2019; Farley et al., 2020*). A solid physical foundation provides greater opportunities for the development of psychological, tactical, and technical skills (*Bompa & Haff, 2009; Farley et al., 2020*). For example, to effectively return the shuttlecock across the entire badminton court, players must execute a wide range of movements, such as swift changes in direction, jumps, rapid arm actions, and lunges from different postural positions (*Phomsoupha & Laffaye, 2015*). Therefore, athletes need to possess not only significant muscular power and strength but also the ability to change direction quickly and maintain dynamic balance. Due to the advantages offered by enhanced physical fitness, a considerable amount of research has been dedicated to improving fitness metrics through various training methods (*Ozmen & Aydogmus, 2016; Falch, Guldteig Rædergård & van den Tillaar, 2019; Thiele et al., 2020; Nuñez et al., 2022; Cid-Calfucura et al., 2023; de Villarreal et al., 2023; Deng et al., 2023*). Among these methods, plyometric training (PT) is frequently recommended by researchers (*Oxfeldt et al., 2019; Eraslan et al., 2021; Ramirez-Campillo et al., 2022, 2023*).

The defining characteristic of PT is the stretch-shortening cycle (SSC), which includes an eccentric movement (lengthening action) followed by a concentric movement (shortening action) (*Heinecke, 2021*). The majority of the PT mechanism consists of two integral components. The first component involves converting the elastic energy accumulated during muscle stretching into power output during concentric contractions (*Wilk et al., 1993*). The second component senses muscular tension and length by using the proprioceptor signals generated during muscle stretching (*Davies, Riemann & Manske, 2015*). These sensory signals then transmit nerve impulses to the spinal cord, relaying information to alpha motor neurons responsible for activating agonist muscles, recruiting motor units, and inhibiting the contraction of antagonist muscles (*Markovic & Mikulic, 2010*). As mentioned above, PT induces a wide range of biomechanical and physiological adaptations. These adaptations make PT a valuable and advantageous training method for enhancing sports performance among athletes (*Cherni et al., 2021; Duchateau & Amiridis, 2023*). The significance of PT has been established through a growing body of scientific research showcasing its efficacy in enhancing various physical fitness factors, such as

muscle power, sprint speed, and change of direction ability, regardless of age or sex (Ramirez-Campillo et al., 2020a, 2020b, 2021a). Nevertheless, the aforementioned research encompassed athletes participating in various non-racket sports, such as soccer, volleyball, and basketball. It is crucial to acknowledge that the impact of PT may vary depending on the players' specific athletic background. As highlighted by Lees (2003), racket sports possess distinct physical demands encompassing various fitness components. Hence, it may not be appropriate to directly apply the findings of these studies to athletes involved in racket sports (Thapa et al., 2021; Sole et al., 2021; Ramirez-Campillo et al., 2021b). Accordingly, the specific impact of PT on racket sports players' physical fitness still awaits discovery.

A systematic review with a meta-analysis can reveal the limitations and gaps within the existing literature on PT. This comprehensive analysis would provide valuable insights for scientists and practitioners. It would also inform them about potential directions for future studies (Ramirez-Campillo et al., 2022). However, there has yet to be a comprehensive review that conducts a meta-analysis of the publications regarding the impact of PT on the physical fitness of racket sports athletes. Therefore, this meta-analysis aims to fill the gap by analyzing the distinct effects of PT compared to control conditions on various components of physical fitness that are relevant to racket sport athletes. Concerning prior meta-analyses (Sole et al., 2021; Deng et al., 2022), we hypothesized that PT would yield greater effects than a control condition in enhancing the physical fitness of athletes involved in racket sports.

METHODS

The research team of this study adhered to the guidelines outlined in the updated Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) statement (Page et al., 2021). This protocol was preregistered (registration number: CRD42023432050) at the International Prospective Register of Systematic Reviews (PROSPERO).

Search strategy

Four databases were accessed for the search: PubMed, Web of Science, SCOPUS, and SPORTDiscus, and there were no limitations placed on publication dates up until June 2, 2023. Previous reviews (Ramirez-Campillo et al., 2021a; Cádiz Gallardo et al., 2023) were adopted to set up our search strategy, which was carried out by employing the Boolean operators "AND" and "OR". The Boolean search syntax displayed below was applied: "plyometric training" OR "ballistic training" OR "jump training" OR "plyometric exercise*" OR "power training" OR "stretch-shortening cycle" AND "racquet sport*" OR "racket sport*" OR "racket player*" OR "badminton" OR "squash" OR "padel" OR "tennis" OR "table tennis" OR "ping pong" OR "racquetball". Moreover, an extensive manual search was performed on both Google Scholar and reference lists from all identified articles to ensure that no pertinent articles were overlooked. Skilled librarians assisted in the data-gathering process to ensure accuracy and completeness. The detailed search strategy is available in Appendix S1. In addition, we reached out to authors to acquire full-text articles or any missing information, such as pre-test and post-test data.

Inclusion and exclusion criteria

Following the PICOS method ([Liberati et al., 2009](#)), we selected the inclusion criteria by (a) population: healthy racket sport players (*e.g.*, tennis, table tennis); (b) intervention: applied a PT intervention lasting >2 weeks, including lower body exercises (*e.g.*, jumping, hopping, skipping) and/or upper body exercises (*e.g.*, medicine ball exercise, push-up) utilizing the SSC; (c) comparator: included a control group; (d) outcome: included at least one of the performance indicators related to physical fitness (*e.g.*, handgrip strength, straight-line sprint test <50 m); and (e) study design: randomized controlled trial.

Studies were excluded if they (a) involved injured athletes (*e.g.*, ankle sprain); (b) had interventions lasting ≤ 2 weeks; (c) did not provide adequate results (*e.g.*, mean and standard deviation); (d) investigated the effects of PT mixed with other training approaches (*e.g.*, balance training), to avoid contamination of the PT effects from other interventions; (e) tested the effects of PT without a control group; and (f) were conducted in languages other than English. In view of translation difficulties and the fact that most of the literature on PT is in English ([Ramirez-Campillo et al., 2018](#)), only English language studies were included.

Study selection and data collection process

During the study's selection procedure, the retrieved publications were initially filtered for duplicates using specialist software (EndNote X9; Clarivate Analytics, London, UK). Following the removal of duplicates, we performed an in-depth review of relevant articles' titles, abstracts, and, finally, entire texts. Two researchers (ND and DH) worked independently throughout every step of the procedure, and any disagreements among the researchers were settled by consensus. Excluded full-text articles were noted, as well as the reasons for their exclusion.

Data items

The data items were common metrics of physical fitness, including but not restricted to (a) muscle power (*e.g.*, jump height), (b) sprint speed (*i.e.*, 0–50 m), (c) muscle strength (*e.g.*, handgrip), (d) change of direction ability (*e.g.*, t-test (without a stimulus)), (e) flexibility (*e.g.*, sit and reach test), and (f) balance (*e.g.*, Y-balance test). Additionally, apart from the mentioned data elements, descriptive characteristics of both the PT interventions (*e.g.*, length, frequency) and the participants (*e.g.*, sex, sport) were extracted, and adverse effects were recorded. To conduct the meta-analysis, we specifically chose original articles that provided data suitable for calculation and utilized consistent outcome measures.

Methodological quality

The methodological quality of each study included in the analysis was evaluated using the PEDro scale ([Maher et al., 2003](#)). There are 11 items on the PEDro checklist, but the first item was not assigned a rating. As a result, the scale used in the evaluation process had a maximum score of 10 and a minimum score of 0. Consistent with previous meta-analyses in the field of PT ([Stojanović et al., 2017](#); [Ramirez-Campillo et al., 2021c](#)), the quality

evaluation was interpreted as follows: ≤ 3 points = poor quality, 4–5 points = moderate quality, 6–10 points = high quality. If trials have been reported on the PEDro database or relevant review articles, the supplied ratings were used in the assessment. Two independent reviewers (ND and DH) conducted the methodological quality assessment. In cases where there were discrepancies in the ratings between the reviewers, a third reviewer was involved to facilitate discussion and reach a consensus (KGS).

Certainty of evidence

Two researchers (ND and DH) adopted the Grading of Recommendations, Assessment, Development, and Evaluation (GRADE) to evaluate the certainty of evidence ([Guyatt et al., 2011](#); [Zhang et al., 2019a, 2019b](#)). Initially, the evidence for each outcome exhibited a high level of certainty. However, it was subsequently downgraded on account of the factors outlined below: (a) risk of bias in studies: if the median PEDro scores were determined to be moderate (<6), the judgments were downgraded by one level; (b) indirectness: the specificity of populations, interventions, comparators, and outcomes ensured by the eligibility criteria automatically granted a default attribution of a low risk of indirectness; (c) risk of publication bias: if there were indications of publication bias, the judgments were downgraded by one level; (d) inconsistency: if the statistical heterogeneity (I^2) was determined to be high ($>75\%$), the judgments were downgraded by one level; (e) imprecision: one level of downgrading was applied when a comparison involved either fewer than 400 participants or had a wide confidence interval (CI) around the effect estimate ([Zeng et al., 2022](#)); if both conditions were present, the certainty of the evidence was downgraded by two levels. In addition, if there were insufficient comparison trials to conduct a meta-analysis, the certainty of the evidence was rated as very low ([Ramirez-Campillo et al., 2022](#)).

Statistical analyses

Meta-analyses were performed when a minimum of three studies provided sufficient data to calculate effect sizes (ES) ([Deng et al., 2022](#); [Ramirez-Campillo et al., 2023](#)). Mean and standard deviation data from pre- and post-intervention measures were used to compute effect sizes for performance outcomes in both the PT and control groups (*i.e.*, Hedges' g). Data were standardized using post-intervention standard deviation values. A random-effects model for meta-analysis was utilized to analyze the pooled data. Additionally, a fixed-effects model was computed and presented to evaluate analytical robustness ([Higgins et al., 2003](#)). The values of ES were accompanied by 95% confidence intervals, and the calculated ES values were interpreted using the following scale: trivial ($ES < 0.2$), small ($0.2 \leq ES \leq 0.6$), moderate ($0.6 < ES \leq 1.2$), large ($1.2 < ES \leq 2.0$), very large ($2.0 < ES \leq 4.0$), and extremely large ($ES > 4.0$) ([Hopkins et al., 2009](#)). In trials involving multiple intervention groups, the sample size of the control group was split proportionately so that all subjects could be compared ([Higgins, Deeks & Altman, 2008](#)). In cases where authors did not submit adequate data (in graphics or missing), we attempted to contact the corresponding authors. The investigation's outcome was left out of the analysis if the authors did not answer our inquiries or were unable to supply the

needed data. Yet, if data was shown in a figure but no numerical data was supplied in the article or tables, we employed the Graph Digitizer software (Digitizelt, Braunschweig, Germany) to extract relevant data from figures or graphs (Drevon, Fursa & Malcolm, 2016). The I^2 statistic was utilized to evaluate heterogeneity; varying degrees of heterogeneity were classified as low, moderate, and high. Specifically, heterogeneity was considered low when it was 25% or below, moderate from 25% to 75%, and high when it exceeded 75% (Higgins & Thompson, 2002). The extended Egger's test was utilized to evaluate the studies' publication bias risk (Egger et al., 1997). Furthermore, a sensitivity analysis was performed when the results of Egger's test were statistically significant. In addition, if it was not feasible to statistically pool the data, the findings were presented in a narrative format.

Subgroup analyses were performed to evaluate the potential impact of moderator factors. Potential sources of heterogeneity that might affect the training outcomes were accounted for in the analyses. These sources were determined *a priori*: program length (weeks), training frequency (weekly sessions), and total number of training sessions. A median split approach was used to divide the participants (Moran et al., 2017, 2018). The participant's sex and age (youth (<18 years old) vs adult (≥ 18 years old)) were also considered as moderator factors. Stratification of the meta-analyses was conducted for each of these factors, and a threshold of $p < 0.05$ was utilized as the significance level to determine statistical significance. The Comprehensive Meta-Analysis software (Version 3.0; Biostat, Englewood, NJ, USA) was used for all of the analyses.

RESULTS

Study selection

As illustrated in Fig. 1, the databases yielded a total of 185 documents, and an additional 20 studies were found through Google Scholar and references. After manually removing duplicates, there were 113 records left. These records' titles and abstracts were screened, leading to the identification of 33 articles eligible for full-text analysis. Following a careful evaluation of all texts, 19 articles were removed, remaining 14 studies satisfied all of the eligibility requirements for the systematic review and meta-analysis.

Methodological quality

After applying the PEDro checklist, nine studies obtained a score of 4 or 5 points, indicating a moderate level of methodological quality. Additionally, five studies attained a score of 6–10 points, indicating a high level of methodological quality (Table 1).

Certainty of evidence

Table 2 displays the GRADE analysis results. The GRADE evaluations indicated that the certainty of the evidence for the outcomes was very low to moderate.

Study characteristics

Table 3 provides a detailed overview of the participants' characteristics and PT programs employed in the included studies. Appendix S2 contains the data utilized in the

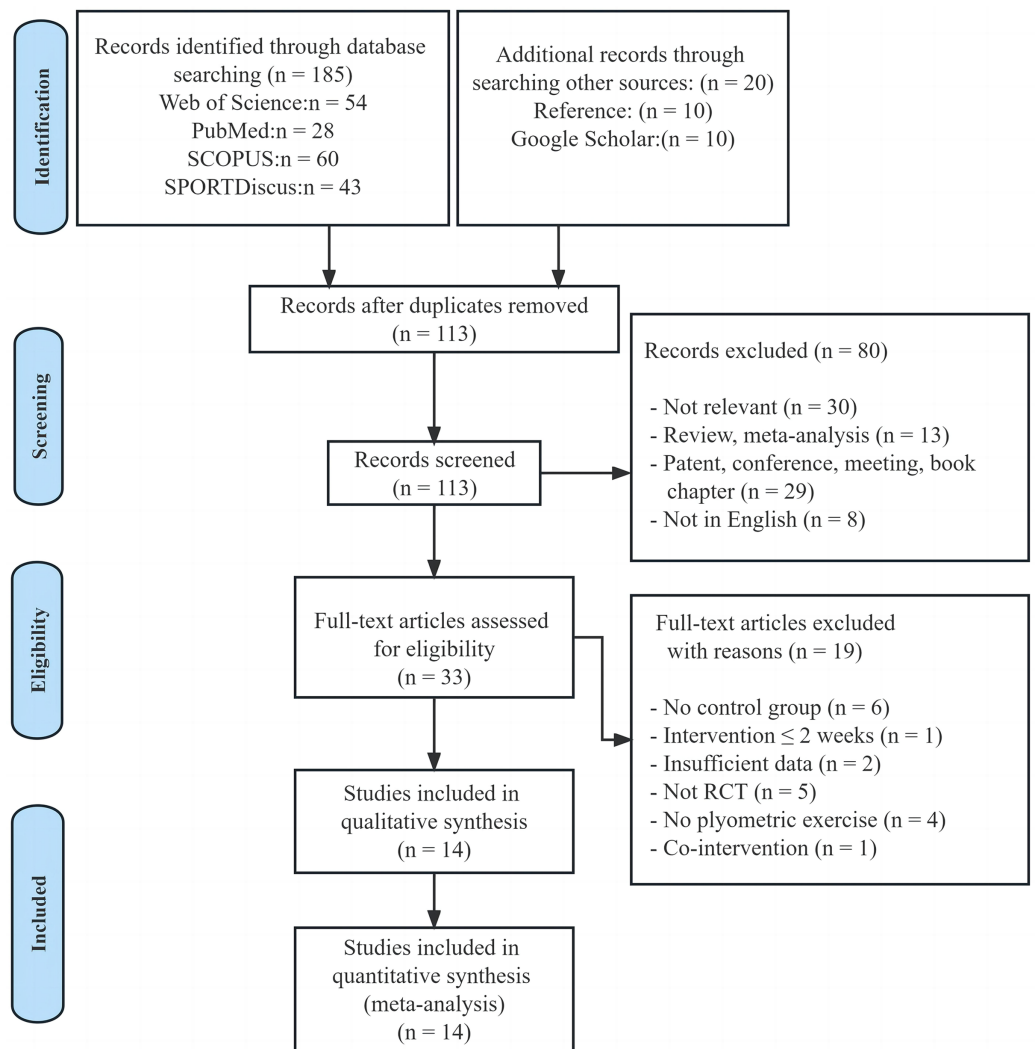


Figure 1 PRISMA flow diagram.

Full-size DOI: 10.7717/peerj.16638/fig-1

meta-analyses. A total of 558 youth and adult athletes participated in the included studies. The intervention groups' sample sizes varied from 8 to 51 players, and their age range was between 12.5 and 25 years. The racket sports athletes included in the study were involved in badminton ($n = 8$), tennis ($n = 3$), and table tennis ($n = 3$).

In general, the intervention period of PT varied from 3 to 12 weeks, with an average duration of 6.6 weeks. The most common period was 8 weeks ($n = 7$). The number of training sessions each week varied from one to three. Overall, the most common training frequencies were two ($n = 6$) or three ($n = 7$) times per week. The total number of scheduled training sessions ranged from 3 to 36 sessions. The training volume ranged from 1 to 5 sets per exercise, with repetitions per set ranging from 7 to 30.

Table 1 Physiotherapy Evidence Database (PEDro) scale ratings.

Study	N° 1	N° 2	N° 3	N° 4	N° 5	N° 6	N° 7	N° 8	N° 9	N° 10	N° 11	Total*	Study quality
<i>Alikhani et al. (2019)</i>	1	1	0	1	0	0	0	1	0	1	1	5	Moderate
<i>Albayati & Kaya (2022)</i>	0	1	0	1	0	0	0	1	0	1	1	5	Moderate
<i>Behringer et al. (2013)</i>	1	1	1	1	0	0	0	1	1	1	1	7	High
<i>Chou (2022)</i>	0	1	0	1	0	0	0	1	1	0	1	4	Moderate
<i>Chandra et al. (2023)</i>	1	1	0	1	0	0	0	1	1	1	1	5	Moderate
<i>Heang et al. (2012)</i>	0	1	0	1	0	0	0	1	0	1	1	5	Moderate
<i>Haghighi et al. (2021)</i>	0	1	0	1	0	0	0	1	1	1	1	6	High
<i>Kaabi, Mabrouk & Passelergue (2022)</i>	0	1	0	1	0	0	0	1	1	1	1	6	High
<i>Narang & Patil (2021)</i>	0	1	0	1	0	0	0	1	1	1	1	6	High
<i>Ozmen & Aydogmus (2017)</i>	1	1	0	1	0	0	0	1	0	1	1	5	Moderate
<i>Panda et al. (2022)</i>	1	1	0	1	0	1	1	1	1	1	1	8	High
<i>Rathore (2016)</i>	1	1	0	1	0	0	0	0	0	1	1	4	Moderate
<i>Salonikidis & Zafeiridis (2008)</i>	0	1	0	1	0	0	0	1	0	1	1	5	Moderate
<i>Zaferanieh et al. (2021)</i>	1	1	0	1	0	0	0	1	0	1	1	5	Moderate

Notes:

A detailed explanation for each PEDro scale item can be accessed at <https://www.pedro.org.au/english/downloads/pedro-scale>.

* From a possible maximal punctuation of 10.

Table 2 GRADE analyses.

Outcomes	Certainty assessment					No of participants and studies	Certainty of evidence (GRADE)
	Risk of bias	Inconsistency	Indirectness	Imprecision	Risk of publication bias		
Muscle power follow-up: range 3 to 12 weeks	Serious ^a	Not serious	Not serious	Serious ^c	Not serious	350 (9 RCTs)	⊕⊕○○ LOW
Muscle strength follow-up: range 8 to 12 weeks	Serious ^a	Not serious	Not serious	Serious ^c	Not serious	155 (6 RCTs)	⊕⊕○○ LOW
Sprint speed follow-up: range 3 to 12 weeks	Not Serious	Not serious	Not serious	Serious ^c	Serious ^e	270 (6 RCTs)	⊕⊕○○ LOW
Change of direction ability follow-up: range 3 to 12 weeks	Not serious	Serious ^b	Not serious	Serious ^c	Not serious	324 (8 RCTs)	⊕○○○ VERY LOW
Reaction time follow-up: range 8 to 12 weeks	Not serious	Not serious	Not serious	Serious ^c	Not serious	122 (4 RCTs)	⊕⊕⊕○ MODERATE

Notes:

GRADE, grading of recommendations assessment, development and evaluation; RCTs, randomized controlled trials.

^a Downgraded by one level due to average PEDro score being moderate (<6).

^b Downgraded by one level due to the high impact of statistical heterogeneity (>75%).

^c Downgraded by one level, as <400 participants were available for a comparison or a wide confidence interval (CI) around the effect estimate; we considered a CI to be wide if it included both a small (0.2–0.6) and large effect size (>1.2–2.0). Downgraded by two levels in case of imprecision based on both assessed points.

^e Downgraded by one level (Egger's test $p < 0.05$).

Table 3 Participant's characteristics and PT interventions in the included studies.

Study	Sport	Participants		Level/experience	Intervention	Type of exercise		Test(s)	Outcome(s)
		Sex	n			Age	PTG		
<i>Heang et al. (2012)</i>	Badminton	Mixed	42	18–20 yrs	Collegiate EG: 2.0 ± 1.4 yrs CG: 1.4 ± 0.8 yrs	Freq: 1 time/week Time: NR Length: 3 weeks	Hops, jumps, bounds, hexagon drill 2–5 sets × 6–15 reps	Agility (Illinois test)	Illinois test ↑
<i>Ozmen & Aydogmus (2017)</i>	Badminton	Mixed	20	12.5 ± 0.2 yrs	NR At least 2 yrs	Freq: 2 times/week Time: NR Length: 6 weeks	Hops, jumps, bounds, hexagon drill 2–5 sets × 5–15 reps	Power (SJ), agility (Illinois test)	SJ ↑, Illinois test ↑
<i>Alikhani et al. (2019)</i>	Badminton	F	22	EG: 2.20 ± 1.30 yrs CG: 22.00 ± 0.84 yrs	Club EG: 2.5 ± 1.0 yrs CG: 3.0 ± 0.9 yrs	Freq: 3 times/week Time: 20 min Length: 6 weeks	Hops, jumps, bounds, triple broad 1–2 sets × 5–30 reps	Balance (Y-balance test)	Y-balance test ↑
<i>Narang & Patil (2021)</i>	Badminton	Mixed	40	18–25 yrs	Club NR	Freq: 2 times/week Time: NR Length: 8 weeks	Ballistic six exercises 3 sets × 10–20 reps	Power (MBT), reaction time	MBT ↑, reaction time ↑
<i>Panda et al. (2022)</i>	Badminton	Mixed	30	EG: 19.06 ± 1.33 yrs CG: 17.5 ± 0.52 yrs	State ≥2 yrs	Freq: 2 times/week Time: 35 min Length: 4 weeks	Jumps, hops, sit ups, step ups, box shuffle 2–5 sets × 5–15 reps	Power (VJ), speed (30 m) agility (t-test)	VJ ↑, t-test ↑, 30 m ↑
<i>Chou (2022)</i>	Badminton	NR	16	19.8 ± 3.34 yrs	Collegiate NR	Freq: 3 times/week Time: 60–90 min Length: 8 weeks	Hops, jumps, side strides, rope ladder side touch 3 sets × 8–12 reps	Power (VJ), speed (30 m), agility (6 × 4 m shuttle run)	VJ ↑, 30 m ↑, 6 × 4 m shuttle run ↑
<i>Albayati & Kaya (2022)</i>	Badminton	NR	21	EG: 13.43 ± 0.53 yrs CG: 13.14 ± 0.69 yrs	NR	Freq: 3 times/week Time: 25–30 min Length: 12 weeks	Hops, jumps, jumping using arms	Power (VJ), agility (t-test), Speed (10 m), reaction time, flexibility (SAR), strength (handgrip)	VJ ↑, t-test ↑, handgrip ↑, 10 m ↔, reaction time ↔, SAR ↔
<i>Chandra et al. (2023)</i>	Badminton	M	102	18–25 yrs	Collegiate ≥3 yrs	Freq: 2 times/week Time: 20 min Length: 3 weeks	Hops, jumps 2–5 sets × 6–15 reps	Power (SBJ), speed (30 m), agility (t-test)	SBJ ↑, t-test ↑, 30 m ↑
<i>Behringer et al. (2013)</i>	Tennis	M	36	15.03 ± 1.64 yrs	Club Averaged 6.15 yrs	Freq: 2 times/week Time: 30–60 min Length: 8 weeks	Jumps, skips, hops, push-ups, medicine ball exercises 2–4 sets × 10–20 reps	Strength (leg press, chest press)	Leg press ↑, chest press ↑

(Continued)

Study	Sport	Participants		Level/experience	Intervention	Type of exercise		Test(s)	Outcome(s)	
		Sex	n			Age	PTG			CG
<i>Rathore (2016)</i>	Tennis	M	60	18–23 yrs	National, state, or inter-varsity NR	Freq: 3 times/week Time: 45 min Length: 8 weeks	Not described	Routine training	Agility (Illinois test)	Illinois test ↑
<i>Salonikidis & Zafiridis (2008)</i>	Tennis	M	64	21.1 ± 1.3 yrs	Novice 2–3 yrs	Freq: 3 times/week Time: NR Length: 9 weeks	Jumps, hops 2 sets × 6–8 reps	Routine training	Power (DJ), strength (Fmax), speed (1.2 m), reaction time ↑	DJ ↑, Fmax ↑, 1.2 m ↑, reaction time ↑
<i>Haghighi et al. (2021)</i>	Table tennis	M	30	24 ± 7 yrs	Provincial and national 7 ± 3 yrs	Freq: 3 times/week Time: NR Length: 8 weeks	Jumps, swimming launch, medicine ball exercises (3 kg) 3–4 sets × 8–30 reps	Routine training	Strength (Chest press, Leg extension)	Chest press ↑, Leg extension ↑
<i>Zaferanieh et al. (2021)</i>	Table tennis	M	30	24 ± 7 yrs	Elite Averaged of 5 yrs	Freq: 3 times/week Time: NR Length: 8 weeks	Jumps, swimming launch, medicine ball exercises (3 kg) 3–4 sets × 8–30 reps	Routine training	Power (SJT, MBP), strength (handgrip), agility (t-test), reaction time	reaction time ↔, handgrip ↔, SJL ↔, MBP ↔, t-test ↑
<i>Kaabi, Mabrouk & Passelergue (2022)</i>	Table tennis	M	45	16–17.4 yrs	Elite >3 yrs	Freq: 2 times/week Time: NR Length: 8 weeks	Jumps, medicine ball exercises 3–4 sets × 5–10 reps	Routine training	power (CMJ), strength (handgrip), speed (5 m), agility (t-test)	Handgrip ↑, CMJ ↑, 5 m ↑, t-test ↑

Note:

NR, not reported; yrs, years; Exp, sports experience; M, male; F, female; Freq, frequency; reps, repetitions; CG, control group; PTG, plyometric training group; reps, repetitions; CMJ, vertical countermovement jump; SBJ, standing broad jump; DJ, drop jump; VJ, vertical jump; MBT, medicine ball throw; SJT, Sargent jump test; SJ, squat jump; MBP, medicine ball put; Fmax, maximum isometric force (knee extension); SAR, sit and reach test; ↑, significant within-group improvement; ↔, non-significant within-group.

Study outcomes

Muscle power

In terms of muscle power, data from six studies were analyzed, which included a total of nine experimental groups and six control groups (pooled $n = 350$). The results indicated a small effect of PT on muscle power (ES = 0.46; 95% CI [0.25–0.67]; $p < 0.001$; $I^2 = 0.0\%$; Egger's test $p = 0.413$; GRADE: low; Fig. 2). When a fixed-effect model was utilized, the pooled estimate remained consistent.

No significant sub-group differences ($p = 0.444$) were observed between ≤ 7 weeks with ≤ 14 total PT sessions (ES = 0.54; 95% CI [0.25–0.83]; within-group $I^2 = 20.6\%$, three study groups) and > 7 weeks with > 14 total PT sessions (ES = 0.38; 95% CI [0.08–0.68]; within-group $I^2 = 0.0\%$, seven study groups) of training. When a fixed-effect model was utilized, the pooled estimate remained consistent.

Similarly, no significant sub-group differences ($p = 0.364$) were noted between ≤ 2 sessions per week (ES = 0.36; 95% CI [0.06–0.66]; within-group $I^2 = 0.0\%$, five study groups) and > 2 sessions per week (ES = 0.56; 95% CI [0.26–0.85]; within-group $I^2 = 0.0\%$, five study groups). When a fixed-effect model was utilized, the pooled estimate remained consistent.

Additionally, between youth (ES = 0.72; 95% CI [0.25–1.22]; within-group $I^2 = 0.0\%$, three study groups) and adult (ES = 0.40; 95% CI [0.17–0.63]; within-group $I^2 = 0.0\%$, seven study groups) racket sport participants, no significant sub-group differences ($p = 0.244$) were found. When a fixed-effect model was utilized, the pooled estimate remained consistent.

Muscle strength

Data from six studies were gathered to evaluate muscle strength, encompassing seven experimental groups and six control groups (pooled $n = 155$). The results displayed a moderate effect of PT on muscle strength (ES = 0.50; 95% CI [0.19–0.82]; $p = 0.002$; $I^2 = 0.0\%$; Egger's test $p = 0.800$; GRADE: low; Fig. 3). When a fixed-effect model was utilized, the pooled estimate remained consistent.

Sprint speed

Sprint speed was assessed based on data from six studies, comprising seven experimental groups and six control groups (pooled $n = 270$). Egger's test yielded a $p = 0.009$. After sensitivity analysis, the removal of one study (Chandra et al., 2023) permitted an Egger's test of $p \geq 0.05$. This led to the final consideration of five studies, which included six experimental and five control groups. PT had a small impact on sprint speed (ES = 0.45; 95% CI [0.15–0.75]; $p = 0.004$; $I^2 = 0.0\%$; GRADE: low; Fig. 4). When a fixed-effect model was utilized, the pooled estimate remained consistent.

Change of direction ability

Data from eight studies were collected for the analysis of change of direction ability, consisting of nine experimental groups and six control groups (pooled $n = 324$). The results indicated a moderate effect of PT on change of direction ability (ES = 0.76; 95% CI [0.27–1.25]; $p = 0.003$; $I^2 = 76.5\%$; Egger's test $p = 0.389$; GRADE: very low; Fig. 5).

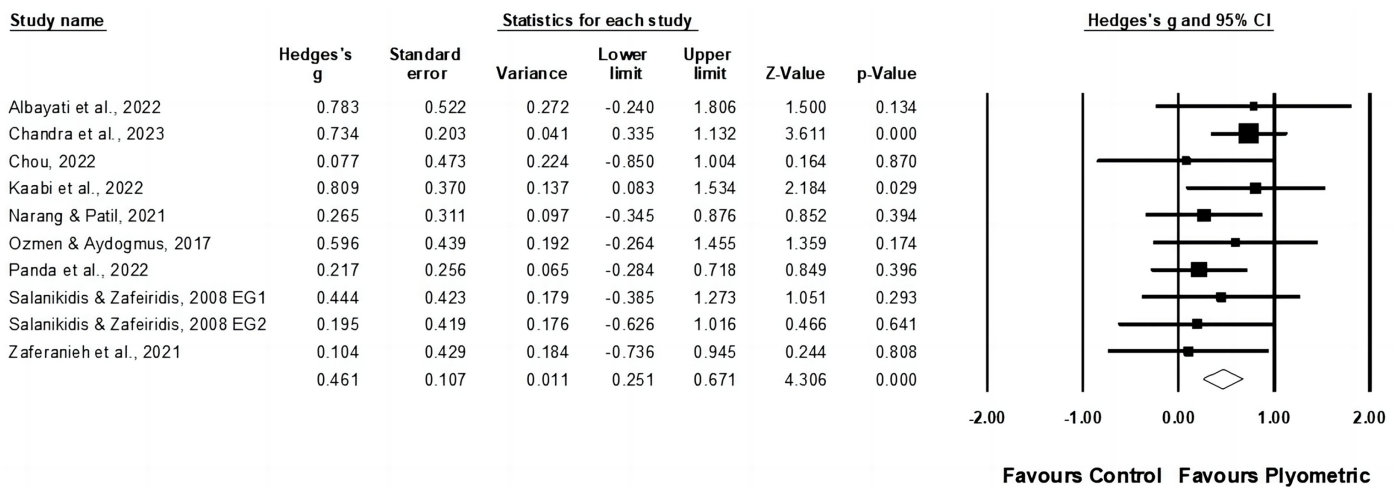


Figure 2 Forest plot of changes in muscle power in racket sport athletes participating in training intervention compared to controls. Values shown are effect sizes (Hedges' g) with 95% confidence intervals (CI). The size of the plotted squares reflects the statistical weight of the study. EG, experimental group *Albayati & Kaya (2022)*, *Chandra et al. (2023)*, *Chou (2022)*, *Kaabi, Mabrouk & Passelergue (2022)*, *Narang & Patil (2021)*, *Ozmen & Aydogmus (2017)*, *Panda et al. (2022)*, *Salanikidis & Zafeiridis (2008)*, *Zaferanieh et al. (2021)*.

Full-size DOI: 10.7717/peerj.16638/fig-2

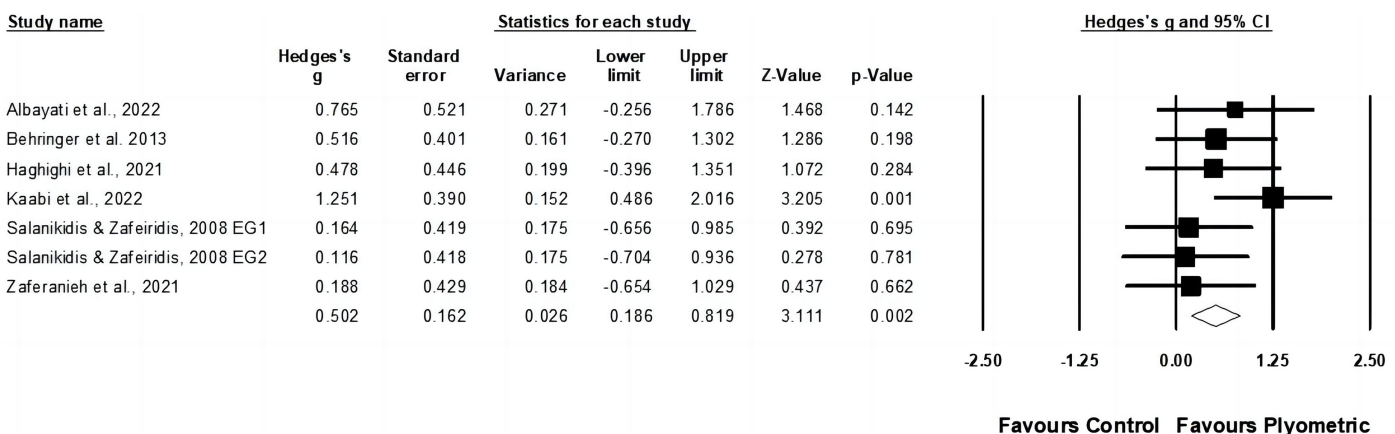


Figure 3 Forest plot of changes in muscle strength in racket sport athletes participating in training intervention compared to controls. Values shown are effect sizes (Hedges' g) with 95% confidence intervals (CI). The size of the plotted squares reflects the statistical weight of the study. EG, experimental group *Albayati & Kaya (2022)*, *Behringer et al. (2013)*, *Haghighi et al. (2021)*, *Kaabi, Mabrouk & Passelergue (2022)*, *Salanikidis & Zafeiridis (2008)*, *Zaferanieh et al. (2021)*.

Full-size DOI: 10.7717/peerj.16638/fig-3

When utilizing a fixed-effect model, a somewhat higher pooled estimate was noted (ES = 0.85, 95% CI [0.62–1.08]; $p < 0.001$).

Reaction time

Four trials with nine experimental groups and six control groups were used to derive data on reaction time (pooled $n = 122$). The results showed a moderate effect of PT on reaction time (ES = 0.67; 95% CI [0.16–1.18]; $p = 0.010$; $I^2 = 46.6%$; Egger's test $p = 0.172$; GRADE:

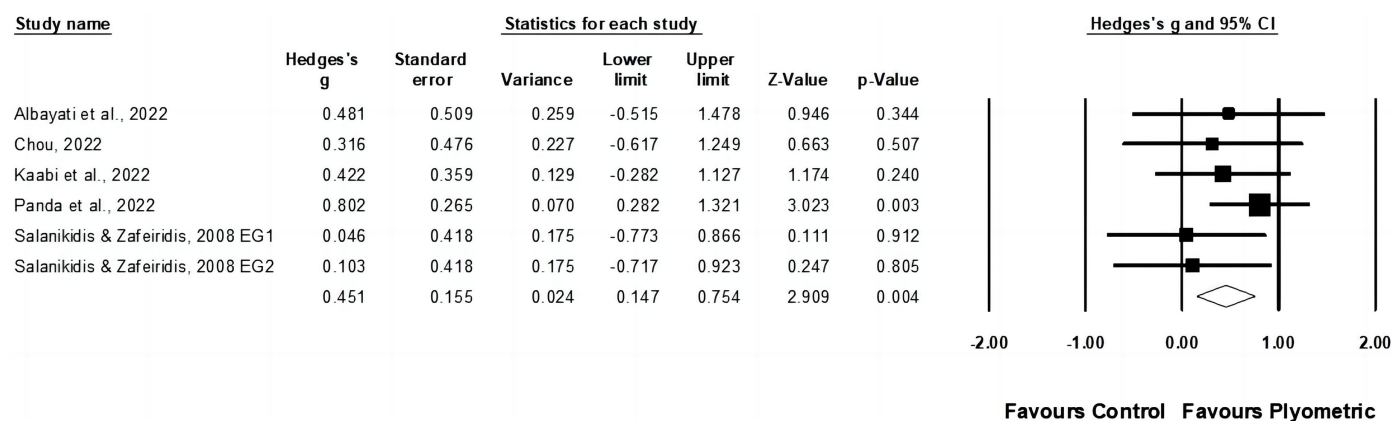


Figure 4 Forest plot of changes in sprint speed in racket sport athletes participating in training intervention compared to controls. Values shown are effect sizes (Hedges' g) with 95% confidence intervals (CI). The size of the plotted squares reflects the statistical weight of the study. EG, experimental group *Albayati & Kaya (2022)*, *Chou (2022)*, *Kaabi, Mabrouk & Passelergue (2022)*, *Panda et al. (2022)*, *Salanikidis & Zafeiridis (2008)*. Full-size [DOI: 10.7717/peerj.16638/fig-4](https://doi.org/10.7717/peerj.16638/fig-4)

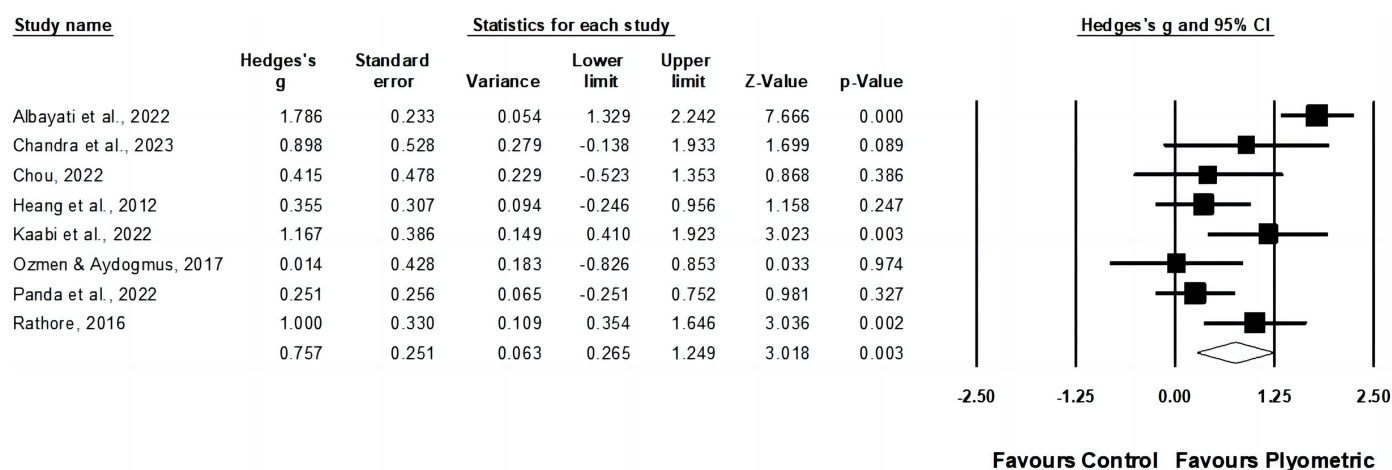


Figure 5 Forest plot of changes in change of direction ability in racket sport athletes participating in training intervention compared to controls. Values shown are effect sizes (Hedges' g) with 95% confidence intervals (CI). The size of the plotted squares reflects the statistical weight of the study *Albayati & Kaya (2022)*, *Chandra et al. (2023)*, *Chou (2022)*, *Heang et al. (2012)*, *Kaabi, Mabrouk & Passelergue (2022)*, *Ozmen & Aydogmus (2017)*, *Panda et al. (2022)*, *Rathore (2016)*. Full-size [DOI: 10.7717/peerj.16638/fig-5](https://doi.org/10.7717/peerj.16638/fig-5)

moderate; Fig. 6). When utilizing a fixed-effect model, a slightly higher pooled estimate was observed (ES = 0.72, 95% CI [0.35–1.08]; $p < 0.001$).

Balance and flexibility

Due to the limited number of studies, balance and flexibility were not incorporated in the meta-analysis. Thus, the certainty of the evidence was automatically rated as very low. A study revealed that the dynamic balance of badminton players significantly improved after 8 weeks of PT (*Alikhani et al., 2019*). However, another study measured flexibility among badminton players. This research demonstrated a non-significant change in the flexibility

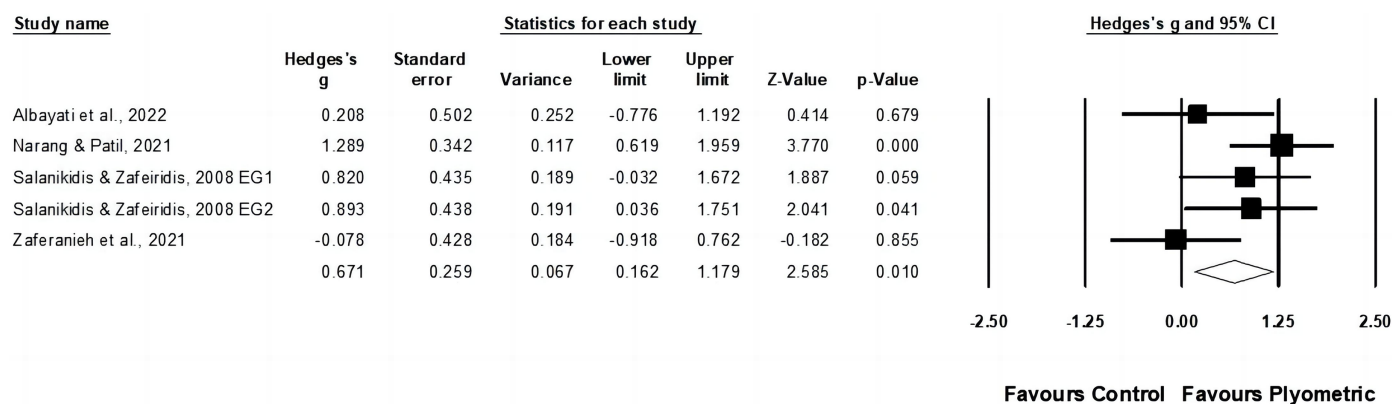


Figure 6 Forest plot of changes in reaction time in racket sport athletes participating in training intervention compared to controls. Values shown are effect sizes (Hedges' g) with 95% confidence intervals (CI). The size of the plotted squares reflects the statistical weight of the study. EG, experimental group *Albayati & Kaya (2022)*, *Narang & Patil (2021)*, *Salanikidis & Zafeiridis (2008)*, *Zaferanieh et al. (2021)*.

Full-size DOI: 10.7717/peerj.16638/fig-6

assessment for the pre-and post-test of the experimental group after 12 weeks of PT (*Albayati & Kaya, 2022*).

Adverse effects

The studies considered in this analysis did not document any cases of injury, soreness, pain, damage, fatigue, or adverse health effects linked to the implemented PT interventions.

DISCUSSION

The present study is the first meta-analysis to look at the effects of PT on racket sports athletes. The findings indicated that PT yielded significant small-to-moderate gains on measures of physical fitness (e.g., muscle power, reaction time) in racket sport players. In most cases, the results exhibited heterogeneity ranging from low to high levels ($I^2 = 0.0-76.5\%$). No substantial changes in mean effects or CIs were observed when employing both random- and fixed-effects models, demonstrating the robustness of the results across all meta-analyses. According to the GRADE assessment, the evaluated outcomes were found to have a very low to moderate level of evidence. Additionally, no definitive evidence was observed for balance and flexibility performance. Moderator analyses were performed for only muscle power due to the availability of at least three studies per moderator. Participants' age and training variables (i.e., length, frequency, and total PT sessions) had no significant moderating effects on muscle power changes following PT.

Muscle power

Power is a vital attribute of muscle function and holds significant importance for athletes participating in competitive sports (*Kraemer & Looney, 2012*; *Möck et al., 2018*). During matches and practice sessions, players consistently have to perform explosive actions, such as quick accelerations or decelerations, rapid changes of direction, and precise strokes

within limited time frames. These requirements emphasize the crucial role of power as a determining factor in achieving success (Reid & Schneiker, 2008; Fernandez-Fernandez, Sanz-Rivas & Mendez-Villanueva, 2009). Our results indicate significant increases in muscle power after the PT program. These findings align with previous meta-analyses that examined athletes from diverse team sports (Slimani et al., 2016; Ramirez-Campillo et al., 2020b, 2021a). In sports such as table tennis, muscle power plays a vital role as it enables players to generate strong muscle contractions, facilitating the execution of various tasks such as exchanging shots with opponents (Zagatto, Papoti & Gobatto, 2008). Indeed, PT has the potential to enhance power production by improving coordination and neuromuscular adaptations (e.g., synchronization, selective muscle activation, and increased recruitment of motor units) (Mirzaei, Norasteh & Asadi, 2013; Chelly, Hermassi & Shephard, 2015). In addition, the hypothesis that PT has a more significant impact on jump performance is frequently proposed due to its foundation in utilizing the SSC to enhance explosive actions. This claim has been supported by several studies (Markovic, 2007; Ramirez-Campillo et al., 2015; Kubo, Ishigaki & Ikebukuro, 2017).

Concerning subgroup analyses, there were no detected between-group differences in muscle power gains after ≤ 7 weeks (with ≤ 14 total sessions) vs > 7 weeks (with > 14 total sessions) or < 2 sessions per week vs ≥ 2 sessions per week. Additionally, no significant differences were observed when comparing the effects between different age groups (youths vs adults). Similarly, previous meta-analyses on PT also did not detect significant differences between subgroups or correlations between training variables and changes in muscle power (Sole et al., 2021; Deng et al., 2023). Nevertheless, according to the chronological adaptation tempo, longer training periods with a higher number of sessions can provide more time for physiological mechanisms to enhance muscle power (Markovic & Mikulic, 2010; Ramirez-Campillo et al., 2018). Moreover, longer PT interventions enable a greater volume of exercises to be completed, resulting in more substantial enhancements in muscle power (Ramirez-Campillo et al., 2015; Asadi et al., 2017). From a practical standpoint, implementing a lower frequency of PT sessions may give players more time to focus on other crucial parts of their preparation (Bouguazzi et al., 2018). However, the current meta-analysis failed to identify any significant subgroup differences regarding PT variables. In addition, consistent with our findings, prior research has demonstrated that PT leads to enhancements in muscle power for athletes, regardless of their age (Sole et al., 2021; Ramirez-Campillo et al., 2020b, 2021a). Collectively, the current evidence suggests that implementing a PT program can lead to notable enhancement in muscle power among racket sport athletes, irrespective of their age and training parameters.

Muscle strength

Muscle strength is a vital factor that influences power and speed in athletic performance (Chanavirut et al., 2017). Our analysis revealed a notable enhancement in muscle strength following PT. These findings align with previous studies conducted on diverse population groups, which also reported that PT was an effective training modality for enhancing muscle strength (de Villarreal, Requena & Newton, 2010; Ramirez-Campillo et al., 2021a;

Morris et al., 2022). The strength improvements induced by PT can be attributed to neural adaptations, including enhancements in firing frequency, synchronization, and motor drive of motor units (*Markovic & Mikulic, 2010*). Furthermore, muscle hypertrophy may also explain PT-induced strength gains (*Grgic, Schoenfeld & Mikulic, 2020*). Of note, grip strength has frequently been utilized as a measure of muscular strength in both the current review (*Zaferanieh et al., 2021; Albayati & Kaya, 2022; Kaabi, Mabrouk & Passelergue, 2022*) and earlier research (*Trosclair et al., 2011; Watanabe et al., 2019*). In fact, grip strength is essential for executing various movements specific to racket sports, as players consistently engage in complex skills while firmly holding the racket (*Fett, Ulbricht & Ferrauti, 2020; Haryanto et al., 2021*). The effects of PT can vary depending on the nature of the training protocol (*Booth & Orr, 2016*). Greater improvements in grip strength are observed using PT with upper-body exercises (e.g., medicine ball exercise) (*Zaferanieh et al., 2021; Kaabi, Mabrouk & Passelergue, 2022*). It is interesting to note that *Albayati & Kaya (2022)* conducted a study primarily utilizing lower-body PT (e.g., jumps, hops) and observed positive results in terms of handgrip strength among young badminton players. Recent research has reported a significant association between handgrip strength and jump performance (*França et al., 2023; Maurya et al., 2023*), which may help explain the findings. Moreover, when analyzing and interpreting handgrip strength during childhood and adolescence, it is essential to consider the influence of biological maturation and growth, since changes in muscle mass and muscle fiber size may be the contributory factors (*Gómez-Campos et al., 2018; Yapici et al., 2022; Wind et al., 2010*).

In addition, one of the included articles observed that weightlifting is more effective than PT in improving muscle strength among table tennis players (*Kaabi, Mabrouk & Passelergue, 2022*). However, a recent meta-analysis comparing weightlifting training with PT indicated that both methods can potentially lead to similar improvements in muscle strength (*Morris et al., 2022*). The question of whether weightlifting training is indeed superior to PT still needs to be confirmed in future studies. From a practical perspective, muscle strength forms the foundation for numerous attributes linked to enhancing an individual's performance in a wide range of both general and sport-specific skills (*Suchomel, Nimphius & Stone, 2016*). This implication underscores the meaningful significance of training interventions designed to enhance muscle strength, where PT offers several advantages for attaining this goal.

Sprint speed

In racket sports, the ability to quickly respond to actions executed by the opponent is crucial, and sprint speed plays a significant role in this regard (*Fernandez-Fernandez et al., 2016*). Following PT, there was a noticeable increase in sprint speed in the present analysis. The findings align with previous meta-analyses conducted on athletes from other sports, such as volleyball and soccer (*van de Hoef et al., 2020; Ramirez-Campillo et al., 2020a, 2021b*). Indeed, PT has practical implications for skilled athletes participating in sports involving initial accelerations, specific explosive actions, and short-distance and/or high-intensity sprints (*de Villarreal, Requena & Cronin, 2012*). Improved sprint performance following PT can be attributed to several factors, including neural factors

(e.g., increased muscle activation level and stimulation of spinal reflex pathways) (Komi & Gollhofer, 1997; Taube, Leukel & Gollhofer, 2012) and physiological factors (e.g., increased muscle force per fiber and cross-sectional area) and/or muscle-tendon unit adaptations (e.g., enhanced effectiveness in storing and releasing elastic energy) (Markovic & Mikulic, 2010). Taken together, these factors may improve SSC efficacy (Ramirez-Campillo et al., 2021c). The enhanced SSC efficacy in the lower body musculature is expected to lead to increased force generation during the concentric phase following a rapid eccentric muscle action, which is a crucial factor for increasing sprint speed (Rimmer & Sleivert, 2000; Ronnestad et al., 2008; de Villarreal, Requena & Cronin, 2012; Hammami et al., 2016). Moreover, maximum sprint speed is significantly correlated with lower-extremity strength and power (Harris et al., 2008; Peñailillo et al., 2016). Improvements in both lower-extremity strength and power have been reported after PT (Ramírez-de la Cruz et al., 2022; Deng et al., 2023).

Furthermore, some researchers highlight that training programs incorporating greater horizontal acceleration (*i.e.*, horizontal jumping and skipping) can optimize gains in sprint performance (de Villarreal, Requena & Cronin, 2012). Particularly, in shorter distances (e.g., ≤ 10 m), the application of horizontal force on the ground is crucial, making a higher PT load in the horizontal direction likely to yield greater benefits during the initial acceleration phase (Chaabene et al., 2021; Ramirez-Campillo et al., 2020a, 2021a). When approaching high speeds, PT with a greater focus on vertical movement may result in greater benefits, especially after vertical workouts with a higher rate of force buildup and shorter ground contact times (Ramirez-Campillo et al., 2020a, 2021c). It should be noted that the bulk of trials included in this meta-analysis used mixed PT regimens, which encompassed both vertical and horizontal drills. This combination of training modalities may contribute to the observed enhancements in linear sprint speed. These observations reinforce the value of PT programs to improve the sprint speed of athletes in racket sports.

Change of direction ability

Change of direction ability is a crucial motor skill essential for success in sports (Brughelli et al., 2008). Compared to control conditions, our findings indicate that PT improves change of direction ability in athletes involved in racket sports. Improvement in change of direction ability through PT is supported by several previous meta-analyses (Asadi et al., 2016; Falch, Guldteig Rædergård & van den Tillaar, 2019; Pardos-Mainer et al., 2021; Ramirez-Campillo et al., 2021a). Several neuromuscular adaptations may explain the improved change of direction ability after PT, such as increased firing frequencies and motor unit recruitment (Aagaard et al., 2002; Arazi, Coetzee & Asadi, 2012).

The physiological changes resulting from these adaptations may lead to a faster rate of force generation and power output. As a result, there could be improvements in the change of direction ability following PT (Sheppard & Young, 2006; Thomas, French & Hayes, 2009). Moreover, PT can enhance eccentric strength in the thigh muscles, which is crucial for deceleration during impulsive movements (Sheppard & Young, 2006). This enhancement enables a rapid transition from eccentric to concentric muscle action in the leg extensors, thus facilitating direction changes (Asadi et al., 2017). Furthermore, a high

sprint speed over short distances is closely correlated with change of direction ability (Nimphius, McGuigan & Newton, 2010; Pereira et al., 2018), and PT often includes exercises or movements that involve quickly decelerating and then explosively accelerating in the opposite direction (Ramírez-Campillo, Andrade & Izquierdo, 2013; Möck & Rosemann, 2023). Overall, the findings presented in this section suggest that PT is useful for improving the change of direction ability of racket sport athletes.

Reaction time

A reduction of milliseconds in reaction time can enable players to execute quicker changes in direction, reach certain points on the court more rapidly, and respond to faster balls during gameplay (Salonikidis & Zafeiridis, 2008). Our meta-analysis showed that PT had a positive effect on reaction time. However, it is difficult to compare our findings to earlier evidence because the effect of PT on reaction time has not been studied to a great extent in the literature. For ball sports (e.g., racket sports), the capacity to respond to visual stimuli is linked to the organization of the motor control system, which relies on the information provided by the perceptual system (McLeod, 1987). Reactive actions in sports encompass a range of offensive and defensive maneuvers, involving accelerated movement, sudden stops, and rapid decelerations, all of which depend on the player's speed of response to stimuli (Yildiz et al., 2020; Prabhu, Kulkarni & Palekar, 2022). Therefore, enhanced reaction time can be an anticipated outcome of PT, as it serves as a means to enhance the sensory-motor system (Turgut et al., 2019). Researchers have observed a positive relationship between change of direction ability and reaction time, suggesting that players with better change of direction speed also tend to react more quickly (Homoud, 2015; Moradi & Esmailzadeh, 2015). Notably, PT has been shown to yield improvements in change of direction ability, as discussed elsewhere in this review (Asadi et al., 2017; Falch, Guldteig Rædergård & van den Tillaar, 2019). Additionally, some studies have assessed the impact of PT on reaction time in other non-racket sports. For example, a twelve-week ballistic-six exercise program was shown to be effective in enhancing reaction time among volleyball players (Turgut et al., 2019). Chottidao et al. (2022) discovered that eight weeks of PT improved reaction time in boxers. Therefore, PT can be considered an effective training modality for enhancing the reaction time of racket sport athletes.

Balance and flexibility

In athletes, balance is important for preventing sports injuries and achieving successful performance in sports skills (Hrysomallis, 2007, 2011). However, among the studies included in our review, only one specifically investigated the balance capacity of badminton players (Alikhani et al., 2019). This research revealed that eight weeks of PT significantly improved the dynamic balance of badminton players. Previously, a meta-analysis conducted by Ramachandran et al. (2021) reported moderate effects of PT on the balance performance of healthy participants. PT offers the benefit of utilizing both the propelling (concentric) and braking (eccentric) phases of the SSC in comparison to other training approaches (Markovic & Mikulic, 2010). This unique aspect of PT leads to improvements in quickness, strength, and power (Taube, Leukel & Gollhofer, 2012).

The importance of adequate lower-extremity muscle strength and power for maintaining or restoring balance in daily activities (e.g., falling) and sports-related tasks (e.g., jump-landing) highlights the significance of PT as an effective means to enhance balance (Blackburn *et al.*, 2000; Muehlbauer, Gollhofer & Granacher, 2015; Vetrovsky *et al.*, 2019).

Maintaining a good level of flexibility not only aids in executing movements effectively but also helps in avoiding injuries (Dantas *et al.*, 2011). However, in our review, only one study examined the flexibility of badminton players (Albayati & Kaya, 2022). The findings from this study demonstrated a non-significant change in the flexibility of the badminton players after twelve weeks of PT. Notably, having a sufficient range of motion in joints is highly significant in racket sports, particularly when executing specific motor gestures that require maximum movement, such as the serve in tennis (Chang, Liu & Chang, 2016) or the smash in badminton (Zhang *et al.*, 2016). Theoretically, PT is beneficial for flexibility. This can be attributed to the activation of the SSC, which combines stretching with muscular contraction. This mechanism potentially explains the positive effects of the eccentric component (O'Sullivan, McAuliffe & DeBurca, 2012).

Nonetheless, there is a lack of data demonstrating the effectiveness of PT on balance and flexibility tasks in racket sports players at this time. PT was reported to have greater effects on balance and flexibility in prior studies, but these interventions were tested on handball players (Hammami *et al.*, 2020), basketball players (Arazi & Asadi, 2011), or soccer players (Ramírez-Campillo *et al.*, 2015). The demands placed on those athletes differ from those on racket sports players (Lees, 2003), implying that their physical capacities and regular training sessions are not comparable to those of racket sports players. Therefore, more research is needed to confirm the impact of PT on balance and flexibility in racket sports athletes.

Limitations

This review has a few limitations that need to be highlighted. Firstly, the current study did not investigate the impact of the PT program on other physical fitness parameters, such as endurance and coordination. Future research in this cohort (*i.e.*, racket sports players) should address these aspects to acquire a deeper understanding. Moreover, due to the scarcity of research (<3) for at least one programming parameter, it was impossible to conduct additional analyses on PT frequency, length, and total sessions for all physical fitness performance measures. Secondly, while the investigations included in the analysis did not explicitly mention any adverse health events related to the PT interventions, it is uncertain if the researchers made a comprehensive effort to document all potential adverse responses. Consequently, to enhance our understanding of the safety aspects associated with this form of training, future research should describe any discomfort, injuries, or adverse events that may be linked to PT. Thirdly, the majority of participants (80%) in the included studies were male players, indicating a need for research involving female athletes on this topic. As a result, the generalizability of our findings is somewhat limited, revealing a gap in the existing literature. Despite the aforementioned limitations, our systematic review with meta-analysis offers a novel and noteworthy value to the current body of

knowledge, shedding light on the advantages of PT in enhancing various essential aspects of physical fitness in racket sports athletes.

Practical applications

The findings of this review have applications for coaches and practitioners. Firstly, it is suggested that PT is part of the training for racket sport athletes, rather than relying solely on high-volume routine training, to improve important indices of physical fitness, specifically muscle power, muscle strength, sprint speed, change of direction ability, and reaction time. Secondly, researchers are strongly encouraged to undertake well-designed studies investigating the effects of PT in other racket sports, such as padel and squash. It is also important to explore the impact of PT specifically among female athletes. These additional studies are crucial to further validate and reinforce the conclusions drawn in this analysis. Thirdly, the utilization of PT is a cost-effective alternative compared to other training strategies, as it requires no or minimal equipment. Typically, PT involves engaging in drills that utilize the athlete's body weight as a load ([Ramirez-Campillo et al., 2020b](#)). This makes it a convenient and accessible training approach for athletes, allowing them to easily incorporate it into their routines.

CONCLUSIONS

This meta-analysis reveals that PT can be implemented as an effective form of training to increase physical fitness in racket sport athletes, including muscle power, muscle strength, sprint speed, change of direction ability, and reaction time. These findings were observed among racket sport athletes involving badminton players, tennis players, and table tennis players. While it is unable to provide precise recommendations for each training parameter, the current review has presented some preliminary data on evidence-based recommendations, such as a training period of three to twelve weeks, a training frequency of one to three sessions per week, a training volume of one to three sets per exercise, and seven to thirty repetitions per set. Future studies are required to clarify the optimal doses and examine interactions among training variables to further promote the physical fitness of this specific population.

ADDITIONAL INFORMATION AND DECLARATIONS

Funding

The authors received no funding for this work.

Competing Interests

The authors declare that they have no competing interests.

Author Contributions

- Nuannuan Deng conceived and designed the experiments, performed the experiments, analyzed the data, prepared figures and/or tables, authored or reviewed drafts of the article, and approved the final draft.

- Kim Geok Soh conceived and designed the experiments, authored or reviewed drafts of the article, and approved the final draft.
- Borhannudin Abdullah conceived and designed the experiments, analyzed the data, authored or reviewed drafts of the article, and approved the final draft.
- Dandan Huang performed the experiments, analyzed the data, prepared figures and/or tables, authored or reviewed drafts of the article, and approved the final draft.

Data Availability

The following information was supplied regarding data availability:

The data used for meta-analysis are available in the [Supplemental File](#).

Supplemental Information

Supplemental information for this article can be found online at <http://dx.doi.org/10.7717/peerj.16638#supplemental-information>.

REFERENCES

- Aagaard P, Simonsen EB, Andersen JL, Magnusson P, Dyhre-Poulsen P. 2002.** Increased rate of force development and neural drive of human skeletal muscle following resistance training. *Journal of Applied Physiology* **93**(4):1318–1326 DOI [10.1152/jappphysiol.00283.2002](https://doi.org/10.1152/jappphysiol.00283.2002).
- Albayati MAK, Kaya Y. 2022.** The effect of 12-week different training methods applied to badminton athletes on some basic motoric properties. *European Journal of Fitness, Nutrition and Sport Medicine Studies* **3**(1):1–9 DOI [10.46827/ejfnsm.v3i1.139](https://doi.org/10.46827/ejfnsm.v3i1.139).
- Alikhani R, Shahrjerdi S, Golpaigany M, Kazemi M. 2019.** The effect of a six-week plyometric training on dynamic balance and knee proprioception in female badminton players. *The Journal of the Canadian Chiropractic Association* **63**(3):144–153.
- Arazi H, Asadi A. 2011.** The effect of aquatic and land plyometric training on strength, sprint, and balance in young basketball players. *Journal of Human Sport and Exercise* **6**(1):101–111 DOI [10.4100/jhse.2011.61.12](https://doi.org/10.4100/jhse.2011.61.12).
- Arazi H, Coetzee B, Asadi A. 2012.** Comparative effect of land and aquatic based plyometric training on the jumping ability and agility of young basketball players. *South African Journal for Research in Sport, Physical Education and Recreation* **34**(2):1–14.
- Asadi A, Arazi H, Ramirez-Campillo R, Moran J, Izquierdo M. 2017.** Influence of maturation stage on agility performance gains after plyometric training: a systematic review and meta-analysis. *The Journal of Strength and Conditioning Research* **31**(9):2609–2617 DOI [10.1519/JSC.0000000000001994](https://doi.org/10.1519/JSC.0000000000001994).
- Asadi A, Arazi H, Young WB, de Villarreal ES. 2016.** The effects of plyometric training on change-of-direction ability: a meta-analysis. *International Journal of Sports Physiology and Performance* **11**(5):563–573 DOI [10.1123/ijsp.2015-0694](https://doi.org/10.1123/ijsp.2015-0694).
- Behringer M, Neuerburg S, Matthews M, Mester J. 2013.** Effects of two different resistance-training programs on mean tennis-serve velocity in adolescents. *Pediatric Exercise Science* **25**(3):370–384 DOI [10.1123/pes.25.3.370](https://doi.org/10.1123/pes.25.3.370).
- Blackburn T, Guskiewicz KM, Petschauer MA, Prentice WE. 2000.** Balance and joint stability: the relative contributions of proprioception and muscular strength. *Journal of Sport Rehabilitation* **9**(4):315–328 DOI [10.1123/jsr.9.4.315](https://doi.org/10.1123/jsr.9.4.315).
- Bompa TO, Haff GG. 2009.** *Periodization: the theory and methodology of training*. Fifth Edition. United States: Human Kinetics.

- Booth MA, Orr R. 2016.** Effects of plyometric training on sports performance. *Strength and Conditioning Journal* **38(1)**:30–37 DOI [10.1519/SSC.0000000000000183](https://doi.org/10.1519/SSC.0000000000000183).
- Bouguazzi R, Chaabene H, Negra Y, Ramirez-Campillo R, Jlalía Z, Mkaouer B, Hachana Y. 2018.** Effects of different plyometric training frequency on measures of athletic performance in prepuberal male soccer players. *The Journal of Strength and Conditioning Research* **34(6)**:1609–1617 DOI [10.1519/JSC.00000000000002486](https://doi.org/10.1519/JSC.00000000000002486).
- Brughelli M, Cronin J, Levin G, Chaouachi A. 2008.** Understanding change of direction ability in sport: a review of resistance training studies. *Sports Medicine* **38(12)**:1045–1063 DOI [10.2165/00007256-200838120-00007](https://doi.org/10.2165/00007256-200838120-00007).
- Cádiz Gallardo MP, de la Fuente FP, Moreno-Azze A, Carrasco Páez L. 2023.** Physiological demands of racket sports: a systematic review. *Frontiers in Psychology* **14**:1149295 DOI [10.3389/fpsyg.2023.1149295](https://doi.org/10.3389/fpsyg.2023.1149295).
- Chaabene H, Negra Y, Moran J, Prieske O, Sammoud S, Ramirez-Campillo R, Granacher U. 2021.** Plyometric training improves not only measures of linear speed, power, and change-of-direction speed but also repeated sprint ability in young female handball players. *The Journal of Strength and Conditioning Research* **35(8)**:2230–2235 DOI [10.1519/JSC.00000000000003128](https://doi.org/10.1519/JSC.00000000000003128).
- Chanavirut R, Udompanich N, Udom P, Yonglitthipagon P, Donpunha W, Nakmareong S, Yamauchi J. 2017.** The effects of strengthening exercises for wrist flexors and extensors on muscle strength and counter-stroke performance in amateur table tennis players. *Journal of Bodywork and Movement Therapies* **21(4)**:1033–1036 DOI [10.1016/j.jbmt.2017.02.002](https://doi.org/10.1016/j.jbmt.2017.02.002).
- Chandra S, Sharma A, Malhotra N, Rizvi MR, Kumari S. 2023.** Effects of plyometric training on the agility, speed, and explosive power of male collegiate badminton players. *Journal of Lifestyle Medicine* **13(1)**:52–58 DOI [10.15280/jlm.2023.13.1.52](https://doi.org/10.15280/jlm.2023.13.1.52).
- Chang BF, Liu CC, Chang HY. 2016.** Characteristic of shoulder and hip rotation range of motion in adolescent tennis players. *The Journal of Sports Medicine and Physical Fitness* **58(4)**:450–456 DOI [10.23736/s0022-4707.16.06714-1](https://doi.org/10.23736/s0022-4707.16.06714-1).
- Chelly MS, Hermassi S, Shephard RJ. 2015.** Effects of in-season short-term plyometric training program on sprint and jump performance of young male track athletes. *The Journal of Strength and Conditioning Research* **29(8)**:2128–2136 DOI [10.1519/JSC.00000000000000860](https://doi.org/10.1519/JSC.00000000000000860).
- Cherni Y, Hammami M, Jelid MC, Aloui G, Suzuki K, Shephard RJ, Chelly MS. 2021.** Neuromuscular adaptations and enhancement of physical performance in female basketball players after 8 weeks of plyometric training. *Frontiers in Physiology* **11**:588787 DOI [10.3389/fphys.2020.588787](https://doi.org/10.3389/fphys.2020.588787).
- Chottidao M, Kuo CH, Tsai SC, Hwang IS, Lin JJ, Tsai YS. 2022.** A comparison of plyometric and jump rope training programs for improving punching performance in junior amateur boxers. *Frontiers in Bioengineering and Biotechnology* **10**:878527 DOI [10.3389/fbioe.2022.878527](https://doi.org/10.3389/fbioe.2022.878527).
- Chou T. 2022.** Whether of plyometric training improves lower limb power, direction-specific movement velocity, and agility in badminton players. *Adaptive Medicine* **14**:32–37 DOI [10.4247/AM.2022.ACC266](https://doi.org/10.4247/AM.2022.ACC266).
- Cid-Calfucura I, Herrera-Valenzuela T, Franchini E, Falco C, Alvial-Moscoso J, Pardo-Tamayo C, Zapata-Huenullán C, Ojeda-Aravena A, Valdés-Badilla P. 2023.** Effects of strength training on physical fitness of olympic combat sports athletes: a systematic review. *International Journal of Environmental Research and Public Health* **20(4)**:3516 DOI [10.3390/ijerph20043516](https://doi.org/10.3390/ijerph20043516).

- Dantas E, Daoud R, Trott A, Nodari R, Conceição M. 2011. Flexibility: components, proprioceptive mechanisms and methods. *Biomedical Human Kinetics* 3(3):39–43 DOI 10.2478/v10101-011-0009-2.
- Davies G, Riemann BL, Manske R. 2015. Current concepts of plyometric exercise. *International Journal of Sports Physical Therapy* 10(6):760.
- de Villarreal SE, Ramos-García D, Calleja-González JE, Alcaraz P, Ramirez-Campillo R. 2023. Comparison of two 8-week training interventions on the athletic performance of padel players. *Kinesiology* 55(1):38–48 DOI 10.26582/k.55.1.5.
- de Villarreal SE, Requena B, Cronin JB. 2012. The effects of plyometric training on sprint performance: a meta-analysis. *The Journal of Strength and Conditioning Research* 26(2):575–584 DOI 10.1519/JSC.0b013e318220fd03.
- de Villarreal ESS, Requena B, Newton RU. 2010. Does plyometric training improve strength performance? A meta-analysis. *Journal of Science and Medicine in Sport* 13(5):513–522 DOI 10.1016/j.jsams.2009.08.005.
- Deng N, Soh KG, Huang D, Abdullah B, Luo S, Rattanakoses W. 2022. Effects of plyometric training on skill and physical performance in healthy tennis players: a systematic review and meta-analysis. *Frontiers in Physiology* 13:1024418 DOI 10.3389/fphys.2022.1024418.
- Deng N, Soh KG, Zaremohzzabieh Z, Abdullah B, Salleh KM, Huang D. 2023. Effects of combined upper and lower limb plyometric training interventions on physical fitness in athletes: a systematic review with meta-analysis. *International Journal of Environmental Research and Public Health* 20(1):482 DOI 10.3390/ijerph20010482.
- Drevon D, Fursa SR, Malcolm AL. 2016. Intercoder reliability and validity of WebPlotDigitizer in extracting graphed data. *Behavior Modification* 41(2):323–339 DOI 10.1177/0145445516673998.
- Duchateau J, Amiridis IG. 2023. Plyometric exercises: optimizing the transfer of training gains to sport performance. *Exercise and Sport Sciences Reviews* 51(4):117–127 DOI 10.1249/JES.0000000000000320.
- Edel A, Song Y, Wiewelhove T, Ferrauti A. 2019. Activity profiles and physiological responses during match play in four popular racquet sports: a literature review. *German Journal of Exercise and Sport Research* 49(3):221–231 DOI 10.1007/s12662-019-00610-4.
- Egger M, Davey Smith G, Schneider M, Minder C. 1997. Bias in meta-analysis detected by a simple, graphical test. *BMJ* 315(7109):629–634 DOI 10.1136/bmj.315.7109.629.
- Eraslan L, Castelein B, Spanhove V, Orhan C, Duzgun I, Cools A. 2021. Effect of plyometric training on sport performance in adolescent overhead athletes: a systematic review. *Sports Health* 13(1):37–44 DOI 10.1177/1941738120938007.
- Falch NH, Guldteig Rædergård H, van den Tillaar R. 2019. Effect of different physical training forms on change of direction ability: a systematic review and meta-analysis. *Sports Medicine-Open* 5(1):1–37 DOI 10.1186/s40798-019-0223-y.
- Farley JB, Stein J, Keogh JW, Woods CT, Milne N. 2020. The relationship between physical fitness qualities and sport-specific technical skills in female, team-based ball players: a systematic review. *Sports Medicine-Open* 6(1):1–20 DOI 10.1186/s40798-020-00245-y.
- Fernandez J, Mendez-Villanueva A, Pluim B. 2006. Intensity of tennis match play. *British Journal of Sports Medicine* 40(5):387–391 DOI 10.1136/bjism.2005.023168.
- Fernandez-Fernandez J, De Villarreal ES, Sanz-Rivas D, Moya M. 2016. The effects of 8-week plyometric training on physical performance in young tennis players. *Pediatric Exercise Science* 28(1):77–86 DOI 10.1123/pes.2015-0019.

- Fernandez-Fernandez J, Sanz-Rivas D, Mendez-Villanueva A. 2009.** A review of the activity profile and physiological demands of tennis match play. *Strength and Conditioning Journal* **31**(4):15–26 DOI [10.1519/SSC.0b013e3181ada1cb](https://doi.org/10.1519/SSC.0b013e3181ada1cb).
- Fett J, Ulbricht A, Ferrauti A. 2020.** Impact of physical performance and anthropometric characteristics on serve velocity in elite junior tennis players. *The Journal of Strength and Conditioning Research* **34**(1):192–202 DOI [10.1519/JSC.0000000000002641](https://doi.org/10.1519/JSC.0000000000002641).
- França C, Marques A, Ihle A, Nuno J, Campos P, Gonçalves F, Martins J, Gouveia É. 2023.** Associations between muscular strength and vertical jumping performance in adolescent male football players. *Human Movement* **24**(2):94–100 DOI [10.5114/hm.2023.117778](https://doi.org/10.5114/hm.2023.117778).
- Gómez-Campos R, Andruske CL, Arruda MD, Sulla-Torres J, Pacheco-Carrillo J, Urra-Albornoz C, Cossio-Bolaños M. 2018.** Normative data for handgrip strength in children and adolescents in the Maule Region, Chile: evaluation based on chronological and biological age. *PLOS ONE* **13**(8):e0201033 DOI [10.1371/journal.pone.0201033](https://doi.org/10.1371/journal.pone.0201033).
- Grgic J, Schoenfeld BJ, Mikulic P. 2020.** Effects of plyometric vs. resistance training on skeletal muscle hypertrophy: a review. *Journal of Sport and Health Science* **10**(5):530–536 DOI [10.1016/j.jshs.2020.06.010](https://doi.org/10.1016/j.jshs.2020.06.010).
- Guyatt G, Oxman AD, Akl EA, Kunz R, Vist G, Brozek J, Norris S, Falck-Ytter Y, Glasziou P, deBeer H. 2011.** GRADE guidelines: 1. Introduction—GRADE evidence profiles and summary of findings tables. *Journal of Clinical Epidemiology* **64**(4):383–394 DOI [10.1016/j.jclinepi.2010.04.026](https://doi.org/10.1016/j.jclinepi.2010.04.026).
- Haghighi AH, Zaferanieh A, Hosseini-Kakhak SA, Maleki A, Esposito F, Cè E, Castellar C, Toro-Román V, Pradas F. 2021.** Effects of power and ballistic training on table tennis players' electromyography changes. *International Journal of Environmental Research and Public Health* **18**(15):7735 DOI [10.3390/ijerph18157735](https://doi.org/10.3390/ijerph18157735).
- Hammami M, Gaamouri N, Suzuki K, Shephard RJ, Chelly MS. 2020.** Effects of upper and lower limb plyometric training program on components of physical performance in young female handball players. *Frontiers in Physiology* **11**:1028 DOI [10.3389/fphys.2020.01028](https://doi.org/10.3389/fphys.2020.01028).
- Hammami M, Negra Y, Aouadi R, Shephard RJ, Chelly MS. 2016.** Effects of an in-season plyometric training program on repeated change of direction and sprint performance in the junior soccer player. *The Journal of Strength and Conditioning Research* **30**(12):3312–3320 DOI [10.1519/JSC.0000000000001470](https://doi.org/10.1519/JSC.0000000000001470).
- Harris NK, Cronin JB, Hopkins WG, Hansen KT. 2008.** Relationship between sprint times and the strength/power outputs of a machine squat jump. *The Journal of Strength and Conditioning Research* **22**(3):691–698 DOI [10.1519/JSC.0b013e31816d8d80](https://doi.org/10.1519/JSC.0b013e31816d8d80).
- Haryanto J, Zulfikal Z, Donie D, Edmizal E. 2021.** Footwork and grip strength: Is it related to smash accuracy. *Journal of Educational and Learning Studies* **4**(1):123–128 DOI [10.32698/01592](https://doi.org/10.32698/01592).
- Heang LJ, Hoe WE, Quin CK, Yin LH. 2012.** Effect of plyometric training on the agility of students enrolled in required college badminton programme. *International Journal of Applied Sports Sciences* **24**(1):18–24 DOI [10.24985/ijass](https://doi.org/10.24985/ijass).
- Heinecke M. 2021.** Literature review: neuromuscular response to plyometric training. *International Journal of Strength and Conditioning* **1**(1).
- Higgins JP, Deeks JJ, Altman DG. 2008.** Special topics in statistics. In: Higgins JP, Green S, eds. *Cochrane Handbook for Systematic Reviews of Interventions*. London: The Cochrane Collaboration, 481–529.
- Higgins JP, Thompson SG. 2002.** Quantifying heterogeneity in a meta-analysis. *Statistics in Medicine* **21**(11):1539–1558 DOI [10.1002/sim.1186](https://doi.org/10.1002/sim.1186).

- Higgins JP, Thompson SG, Deeks JJ, Altman DG. 2003.** Measuring inconsistency in meta-analyses. *BMJ* 327(7414):557–560 DOI 10.1136/bmj.327.7414.557.
- Homoud MNA. 2015.** Relationships between illinois agility test and reaction time in male athletes. *The Swedish Journal of Scientific Research* 2(3):28–33.
- Hopkins WG, Marshall SW, Batterham AM, Hanin J. 2009.** Progressive statistics for studies in sports medicine and exercise science. *Medicine & Science in Sports & Exercise* 41(1):3–13 DOI 10.1249/MSS.0b013e31818cb278.
- Hrysomallis C. 2007.** Relationship between balance ability, training and sports injury risk. *Sports Medicine* 37(6):547–556 DOI 10.2165/00007256-200737060-00007.
- Hrysomallis C. 2011.** Balance ability and athletic performance. *Sports Medicine* 41(3):221–232 DOI 10.2165/11538560-000000000-00000.
- Kaabi S, Mabrouk RH, Passelergue P. 2022.** Weightlifting is better than plyometric training to improve strength, counter movement jump, and change of direction skills in Tunisian elite male junior table tennis players. *Journal of Strength and Conditioning Research* 36(10):2912–2919 DOI 10.1519/JSC.0000000000003972.
- Komi PV, Gollhofer A. 1997.** Stretch reflexes can have an important role in force enhancement during SSC exercise. *Journal of Applied Biomechanics* 13(4):451–460 DOI 10.1123/jab.13.4.451.
- Kraemer WJ, Looney DP. 2012.** Underlying mechanisms and physiology of muscular power. *Strength and Conditioning Journal* 34(6):13–19 DOI 10.1519/SSC.0b013e318270616d.
- Kubo K, Ishigaki T, Ikebukuro T. 2017.** Effects of plyometric and isometric training on muscle and tendon stiffness in vivo. *Physiological Reports* 5(15):e13374 DOI 10.14814/phy2.13374.
- Lees A. 2003.** Science and the major racket sports: a review. *Journal of Sports Sciences* 21(9):707–732 DOI 10.1080/0264041031000140275.
- Liberati A, Altman DG, Tetzlaff J, Mulrow C, Gøtzsche PC, Ioannidis J, Clarke M, Devereaux PJ, Kleijnen J, Moher D. 2009.** The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: explanation and elaboration. *Annals of Internal Medicine* 151(4):W–65 DOI 10.7326/0003-4819-151-4-200908180-00136.
- Maher CG, Sherrington C, Herbert RD, Moseley AM, Elkins M. 2003.** Reliability of the PEDro scale for rating quality of randomized controlled trials. *Physical Therapy* 83(8):713–721 DOI 10.1093/ptj/83.8.713.
- Markovic G. 2007.** Does plyometric training improve vertical jump height? A meta-analytical review. *British Journal of Sports Medicine* 41(6):349–355 DOI 10.1136/bjism.2007.035113.
- Markovic G, Mikulic P. 2010.** Neuro-musculoskeletal and performance adaptations to lower-extremity plyometric training. *Sports Medicine* 40(10):859–895 DOI 10.2165/11318370-000000000-00000.
- Maurya PS, Sisneros KP, Johnson EB, Palmer TB. 2023.** Reliability of handgrip strength measurements and their relationship with muscle power. *The Journal of Sports Medicine and Physical Fitness* 63(7):805–811 DOI 10.23736/S0022-4707.23.14820-1.
- McLeod P. 1987.** Visual reaction time and high-speed ball games. *Perception* 16(1):49–59 DOI 10.1068/p160049.
- Mirzaei B, Norasteh AA, Asadi A. 2013.** Neuromuscular adaptations to plyometric training: depth jump vs. countermovement jump on sand. *Sport Sciences for Health* 9(3):145–149 DOI 10.1007/s11332-013-0161-x.

- Möck S, Hartmann R, Wirth K, Rosenkranz G, Mickel C. 2018. Correlation of dynamic strength in the standing calf raise with sprinting performance in consecutive sections up to 30 meters. *Research in Sports Medicine* 26(4):474–481 DOI 10.1080/15438627.2018.1492397.
- Möck S, Rosemann A. 2023. Effects of a 5-week plyometric intervention for competitive young table tennis players. *German Journal of Exercise and Sport Research* 53(1):1–9 DOI 10.1007/s12662-022-00853-8.
- Moradi A, Esmailzadeh S. 2015. Association between reaction time, speed and agility in schoolboys. *Sport Sciences for Health* 11(3):251–256 DOI 10.1007/s11332-015-0230-4.
- Moran J, Sandercock G, Ramirez-Campillo R, Clark CCT, Fernandes JFT, Drury B. 2018. A meta-analysis of resistance training in female youth: its effect on muscular strength, and shortcomings in the literature. *Sports Medicine* 48(7):1661–1671 DOI 10.1007/s40279-018-0914-4.
- Moran J, Sandercock GR, Ramirez-Campillo R, Meylan C, Collison J, Parry DA. 2017. A meta-analysis of maturation-related variation in adolescent boy athletes' adaptations to short-term resistance training. *Journal of Sports Sciences* 35(11):1041–1051 DOI 10.1080/02640414.2016.1209306.
- Morris SJ, Oliver JL, Pedley JS, Haff GG, Lloyd RS. 2022. Comparison of weightlifting, traditional resistance training and plyometrics on strength, power and speed: a systematic review with meta-analysis. *Sports Medicine* 52(7):1533–1554 DOI 10.1007/s40279-021-01627-2.
- Muehlbauer T, Gollhofer A, Granacher U. 2015. Associations between measures of balance and lower-extremity muscle strength/power in healthy individuals across the lifespan: a systematic review and meta-analysis. *Sports Medicine* 45(12):1671–1692 DOI 10.1007/s40279-015-0390-z.
- Narang S, Patil D. 2021. Determination of ballistic six exercises and theraband exercises on physical performance in badminton players: a randomized controlled clinical trial. *Journal of Pharmaceutical Research International* 33(49A):281–291 DOI 10.9734/jpri/2021/v33i49A33331.
- Nimphius S, McGuigan MR, Newton RU. 2010. Relationship between strength, power, speed, and change of direction performance of female softball players. *The Journal of Strength and Conditioning Research* 24(4):885–895 DOI 10.1519/JSC.0b013e3181d4d41d.
- Núñez J, Suarez-Arrones L, de Hoyo M, Loturco I. 2022. Strength training in professional soccer: effects on short-sprint and jump performance. *International Journal of Sports Medicine* 43(06):485–495 DOI 10.1055/a-1653-7350.
- O'Sullivan K, McAuliffe S, DeBurca N. 2012. The effects of eccentric training on lower limb flexibility: a systematic review. *British Journal of Sports Medicine* 46(12):838–845 DOI 10.1136/bjsports-2011-090835.
- Oxfeldt M, Overgaard K, Hvid LG, Dalgas U. 2019. Effects of plyometric training on jumping, sprint performance, and lower body muscle strength in healthy adults: a systematic review and meta-analyses. *Scandinavian Journal of Medicine and Science in Sports* 29(10):1453–1465 DOI 10.1111/sms.13487.
- Ozmen T, Aydogmus M. 2016. Effect of core strength training on dynamic balance and agility in adolescent badminton players. *Journal of Bodywork and Movement Therapies* 20(3):565–570 DOI 10.1016/j.jbmt.2015.12.006.
- Ozmen T, Aydogmus M. 2017. Effect of plyometric training on jumping performance and agility in adolescent badminton players. *Turkish Journal of Sport and Exercise* 19(2):222–227 DOI 10.15314/tsed.319749.
- Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, Shamseer L, Tetzlaff JM, Akl EA, Brennan SE, Chou R, Glanville J, Grimshaw JM, Hróbjartsson A, Lalu MM, Li T, Loder EW, Mayo-Wilson E, McDonald S, McGuinness LA, Stewart LA,

- Thomas J, Tricco AC, Welch VA, Whiting P, Moher D. 2021. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *International Journal of Surgery* **88**(Suppl 1):105906 DOI [10.1016/j.ijisu.2021.105906](https://doi.org/10.1016/j.ijisu.2021.105906).
- Panda M, Rizvi MR, Sharma A, Sethi P, Ahmad I, Kumari S. 2022. Effect of electromyostimulation and plyometrics training on sports-specific parameters in badminton players. *Sports Medicine and Health Science* **4**(4):280–286 DOI [10.1016/j.smhs.2022.08.002](https://doi.org/10.1016/j.smhs.2022.08.002).
- Pardos-Mainer E, Lozano D, Torrontegui-Duarte M, Cartón-Llorente A, Roso-Moliner A. 2021. Effects of strength vs. plyometric training programs on vertical jumping, linear sprint and change of direction speed performance in female soccer players: a systematic review and meta-analysis. *International Journal of Environmental Research and Public Health* **18**(2):401 DOI [10.3390/ijerph18020401](https://doi.org/10.3390/ijerph18020401).
- Peñailillo L, Espíldora F, Jannas-Vela S, Mujika I, Zbinden-Foncea H. 2016. Muscle strength and speed performance in youth soccer players. *Journal of Human Kinetics* **50**(1):203–210 DOI [10.1515/hukin-2015-0157](https://doi.org/10.1515/hukin-2015-0157).
- Pereira LA, Nimphius S, Kobal R, Kitamura K, Turisco LAL, Orsi RC, Cal Abad César C, Loturco I. 2018. Relationship between change of direction, speed, and power in male and female national olympic team handball athletes. *The Journal of Strength and Conditioning Research* **32**(10):2987–2994 DOI [10.1519/JSC.0000000000002494](https://doi.org/10.1519/JSC.0000000000002494).
- Phomsoupha M, Laffaye G. 2015. The science of badminton: game characteristics, anthropometry, physiology, visual fitness and biomechanics. *Sports Medicine* **45**(4):473–495 DOI [10.1007/s40279-014-0287-2](https://doi.org/10.1007/s40279-014-0287-2).
- Prabhu C, Kulkarni N, Palekar TJ. 2022. Influence of agility and core endurance on visual reaction time in amateur male badminton players. *Physiotherapy Practice and Research* **43**(2):199–204 DOI [10.3233/PPR-210578](https://doi.org/10.3233/PPR-210578).
- Ramachandran AK, Singh U, Ramirez-Campillo R, Clemente FM, Afonso J, Granacher U. 2021. Effects of plyometric jump training on balance performance in healthy participants: a systematic review with meta-analysis. *Frontiers in Physiology* **12**:730945 DOI [10.3389/fphys.2021.730945](https://doi.org/10.3389/fphys.2021.730945).
- Ramírez-Campillo R, Andrade DC, Izquierdo M. 2013. Effects of plyometric training volume and training surface on explosive strength. *The Journal of Strength and Conditioning Research* **27**(10):2714–2722 DOI [10.1519/JSC.0b013e318280c9e9](https://doi.org/10.1519/JSC.0b013e318280c9e9).
- Ramirez-Campillo R, Andrade DC, Nikolaidis PT, Moran J, Clemente FM, Chaabene H, Comfort P. 2020b. Effects of plyometric jump training on vertical jump height of volleyball players: a systematic review with meta-analysis of randomized-controlled trial. *Journal of Sports Science and Medicine* **19**(3):489–499 DOI [10.25932/publishup-52589](https://doi.org/10.25932/publishup-52589).
- Ramirez-Campillo R, Castillo D, Raya-González J, Moran J, de Villarreal ES, Lloyd RS. 2020a. Effects of plyometric jump training on jump and sprint performance in young male soccer players: a systematic review and meta-analysis. *Sports Medicine* **50**(12):2125–2143 DOI [10.1007/s40279-020-01337-1](https://doi.org/10.1007/s40279-020-01337-1).
- Ramírez-Campillo R, Gallardo F, Henriquez-Olguín C, Meylan CMP, Martínez C, Álvarez C, Caniuqueo A, Cadore EL, Izquierdo M. 2015. Effect of vertical, horizontal, and combined plyometric training on explosive, balance, and endurance performance of young soccer players. *The Journal of Strength and Conditioning Research* **29**(7):1784–1795 DOI [10.1519/JSC.0000000000000827](https://doi.org/10.1519/JSC.0000000000000827).
- Ramirez-Campillo R, Garcia-Hermoso A, Moran J, Chaabene H, Negra Y, Scanlan AT. 2021a. The effects of plyometric jump training on physical fitness attributes in basketball players: a meta-analysis. *Journal of Sport and Health Science* **11**(6):656–670 DOI [10.1016/j.jshs.2020.12.005](https://doi.org/10.1016/j.jshs.2020.12.005).

- Ramirez-Campillo R, García-de-Alcaraz A, Chaabene H, Moran J, Negra Y, Granacher U. 2021b. Effects of plyometric jump training on physical fitness in amateur and professional volleyball: a meta-analysis. *Frontiers in Physiology* 12:636140 DOI 10.3389/fphys.2021.636140.
- Ramirez-Campillo R, Gentil P, Negra Y, Grgic J, Girard O. 2021c. Effects of plyometric jump training on repeated sprint ability in athletes: a systematic review and meta-analysis. *Sports Medicine* 51(10):2165–2179 DOI 10.1007/s40279-021-01479-w.
- Ramirez-Campillo R, Perez-Castilla A, Thapa RK, Afonso J, Clemente FM, Colado JC, de Villarreal ES, Chaabene H. 2022. Effects of plyometric jump training on measures of physical fitness and sport-specific performance of water sports athletes: a systematic review with meta-analysis. *Sports Medicine-Open* 8(1):108 DOI 10.1186/s40798-022-00502-2.
- Ramirez-Campillo R, Thapa RK, Afonso J, Perez-Castilla A, Bishop C, Byrne PJ, Granacher U. 2023. Effects of plyometric jump training on the reactive strength index in healthy individuals across the lifespan: a systematic review with meta-analysis. *Sports Medicine* 53(5):1029–1053 DOI 10.1007/s40279-023-01825-0.
- Ramirez-Campillo R, Álvarez C, García-Hermoso A, Ramírez-Vélez R, Gentil P, Asadi A, Chaabene H, Moran J, Meylan C, García-de-Alcaraz A, Sanchez-Sanchez J, Nakamura FY, Granacher U, Kraemer W, Izquierdo M. 2018. Methodological characteristics and future directions for plyometric jump training research: a scoping review. *Sports Medicine* 48(5):1059–1081 DOI 10.1007/s40279-018-0870-z.
- Ramírez-delaCruz M, Bravo-Sánchez A, Esteban-García P, Jiménez F, Abián-Vicén J. 2022. Effects of plyometric training on lower body muscle architecture, tendon structure, stiffness and physical performance: a systematic review and meta-analysis. *Sports Medicine-Open* 8(1):40 DOI 10.1186/s40798-022-00431-0.
- Rathore MS. 2016. Effects of plyometric training and resistance training on agility of tennis players. *Indian Journal of Physical Education, Sports Medicine & Exercise Science* 16:32–34.
- Reid M, Schneiker K. 2008. Strength and conditioning in tennis: current research and practice. *Journal of Science and Medicine in Sport* 11(3):248–256 DOI 10.1016/j.jsams.2007.05.002.
- Rimmer E, Sleivert G. 2000. Effects of a plyometrics intervention program on sprint performance. *The Journal of Strength and Conditioning Research* 14(3):295–301 DOI 10.1519/1533-4287(2000)014<0295:EOAPIP>2.0.CO;2.
- Rønnestad BR, Kvamme NH, Sunde A, Raastad T. 2008. Short-term effects of strength and plyometric training on sprint and jump performance in professional soccer players. *The Journal of Strength and Conditioning Research* 22(3):773–780 DOI 10.1519/JSC.0b013e31816a5e86.
- Salonikidis K, Zafeiridis A. 2008. The effects of plyometric, tennis-drills, and combined training on reaction, lateral and linear speed, power, and strength in novice tennis players. *The Journal of Strength and Conditioning Research* 22(1):182–191 DOI 10.1519/JSC.0b013e31815f57ad.
- Sheppard JM, Young WB. 2006. Agility literature review: classifications, training and testing. *Journal of Sports Sciences* 24(9):919–932 DOI 10.1080/02640410500457109.
- Slimani M, Chamari K, Miarka B, Del Vecchio FB, Chéour F. 2016. Effects of plyometric training on physical fitness in team sport athletes: a systematic review. *Journal of Human Kinetics* 53(1):231–247 DOI 10.1515/hukin-2016-0026.
- Sole S, Ramírez-Campillo R, Andrade DC, Sanchez-Sanchez J. 2021. Plyometric jump training effects on the physical fitness of individual-sport athletes: a systematic review with meta-analysis. *PeerJ* 9(17):e11004 DOI 10.7717/peerj.11004.
- Stojanović E, Ristić V, McMaster DT, Milanović Z. 2017. Effect of plyometric training on vertical jump performance in female athletes: a systematic review and meta-analysis. *Sports Medicine* 47(5):975–986 DOI 10.1007/s40279-016-0634-6.

- Suchomel TJ, Nimphius S, Stone MH. 2016.** The importance of muscular strength in athletic performance. *Sports Medicine* **46(10)**:1419–1449 DOI [10.1007/s40279-016-0486-0](https://doi.org/10.1007/s40279-016-0486-0).
- Taube W, Leukel C, Gollhofer A. 2012.** How neurons make us jump: the neural control of stretch-shortening cycle movements. *Exercise and Sport Sciences Reviews* **40(2)**:106–115 DOI [10.1097/JES.0b013e31824138da](https://doi.org/10.1097/JES.0b013e31824138da).
- Thapa RK, Lum D, Moran J, Ramirez-Campillo R. 2021.** Effects of complex training on sprint, jump, and change of direction ability of soccer players: a systematic review and meta-analysis. *Frontiers in Psychology* **11**:627869 DOI [10.3389/fpsyg.2020.627869](https://doi.org/10.3389/fpsyg.2020.627869).
- Thiele D, Prieske O, Chaabene H, Granacher U. 2020.** Effects of strength training on physical fitness and sport-specific performance in recreational, sub-elite, and elite rowers: a systematic review with meta-analysis. *Journal of Sports Sciences* **38(10)**:1186–1195 DOI [10.1080/02640414.2020.1745502](https://doi.org/10.1080/02640414.2020.1745502).
- Thomas K, French D, Hayes PR. 2009.** The effect of two plyometric training techniques on muscular power and agility in youth soccer players. *The Journal of Strength and Conditioning Research* **23(1)**:332–335 DOI [10.1519/JSC.0b013e318183a01a](https://doi.org/10.1519/JSC.0b013e318183a01a).
- Trosclair D, Bellar D, Judge LW, Smith J, Mazerat N, Brignac A. 2011.** Hand-grip strength as a predictor of muscular strength and endurance. *The Journal of Strength and Conditioning Research* **25**:S99 DOI [10.1097/01.JSC.0000395736.42557.bc](https://doi.org/10.1097/01.JSC.0000395736.42557.bc).
- Turgut E, Cinar-Medeni O, Colakoglu FF, Baltaci G. 2019.** Ballistic six upper-extremity plyometric training for the pediatric volleyball players. *The Journal of Strength and Conditioning Research* **33(5)**:1305–1310 DOI [10.1519/JSC.0000000000002060](https://doi.org/10.1519/JSC.0000000000002060).
- van de Hoef PA, Brauers JJ, van Smeden M, Backx FJG, Brink MS. 2020.** The effects of lower-extremity plyometric training on soccer-specific outcomes in adult male soccer players: a systematic review and meta-analysis. *International Journal of Sports Physiology and Performance* **15(1)**:3–17 DOI [10.1123/ijsp.2019-0565](https://doi.org/10.1123/ijsp.2019-0565).
- Vetrovsky T, Steffl M, Stastny P, Tufano JJ. 2019.** The efficacy and safety of lower-limb plyometric training in older adults: a systematic review. *Sports Medicine* **49(1)**:113–131 DOI [10.1007/s40279-018-1018-x](https://doi.org/10.1007/s40279-018-1018-x).
- Watanabe Y, Yamada Y, Yoshida T, Matsui T, Seo K, Azuma Y, Hiramoto M, Miura Y, Fukushima H, Shimazu A, Eto T, Saotome H, Kida N, Morihara T. 2019.** Relationship between physical fitness at the end of pre-season and the in-season game performance in Japanese female professional baseball players. *The Journal of Strength and Conditioning Research* **33(6)**:1580–1588 DOI [10.1519/JSC.0000000000002024](https://doi.org/10.1519/JSC.0000000000002024).
- Wilk KE, Voight ML, Keirns MA, Gambetta V, Andrews JR, Dillman C. 1993.** Stretch-shortening drills for the upper extremities: theory and clinical application. *Journal of Orthopaedic and Sports Physical Therapy* **17(5)**:225–239 DOI [10.2519/jospt.1993.17.5.225](https://doi.org/10.2519/jospt.1993.17.5.225).
- Wind AE, Takken T, Helder PJ, Engelbert RH. 2010.** Is grip strength a predictor for total muscle strength in healthy children, adolescents, and young adults? *European Journal of Pediatrics* **169(3)**:281–287 DOI [10.1007/s00431-009-1010-4](https://doi.org/10.1007/s00431-009-1010-4).
- Wörner EA, Safran MR. 2021.** Racquet sports: tennis, badminton, racquetball, squash. In: Rocha Piedade S, Neyret P, Espregueira-Mendes J, Cohen M, Hutchinson MR, eds. *Specific Sports-Related Injuries*. Cham: Springer.
- Yapici H, Gulu M, Yagin FH, Eken O, Gabrys T, Knappova V. 2022.** Exploring the relationship between biological maturation level, muscle strength, and muscle power in adolescents. *Biology* **11(12)**:1722 DOI [10.3390/biology11121722](https://doi.org/10.3390/biology11121722).

- Yildiz S, Ates O, Gelen E, Cirak E, Bakici D, Sert V, Kayihan G, Özkan A. 2020.** The relationship between reaction time, agility and speed performance in high-level soccer players. *Acta Medica Mediterranea* 36(5):2923–2927 DOI [10.19193/0393-6384_2020_5_448](https://doi.org/10.19193/0393-6384_2020_5_448).
- Zaferanieh A, Haghighi AH, Kakhak SAH, Maleki A, Cè E, Esposito F. 2021.** Effect of ballistic and power training on performance adaptations of elite table tennis players. *Sport Sciences for Health* 17(1):181–190 DOI [10.1007/s11332-020-00671-1](https://doi.org/10.1007/s11332-020-00671-1).
- Zagatto AM, Papoti M, Gobatto CA. 2008.** Validity of critical frequency test for measuring table tennis aerobic endurance through specific protocol. *Journal of Sports Science and Medicine* 7(4):461–466.
- Zeng L, Brignardello-Petersen R, Hultcrantz M, Mustafa RA, Murad MH, Iorio A, Traversy G, Akl EA, Mayer M, Schünemann HJ, Guyatt GH. 2022.** GRADE guidance 34: update on rating imprecision using a minimally contextualized approach. *Journal of Clinical Epidemiology* 150(20):216–224 DOI [10.1016/j.jclinepi.2022.07.014](https://doi.org/10.1016/j.jclinepi.2022.07.014).
- Zhang Y, Alonso-Coello P, Guyatt GH, Yepes-Nuñez JJ, Akl EA, Hazlewood G, Pardo-Hernandez H, Etxeandia-Ikobaltzeta I, Qaseem A, Williams JW Jr, Tugwell P, Flottorp S, Chang Y, Zhang Y, Mustafa RA, Rojas MX, Schünemann HJ. 2019a.** GRADE guidelines: 19. Assessing the certainty of evidence in the importance of outcomes or values and preferences—risk of bias and indirectness. *Journal of Clinical Epidemiology* 111(4):94–104 DOI [10.1016/j.jclinepi.2018.01.013](https://doi.org/10.1016/j.jclinepi.2018.01.013).
- Zhang Y, Coello PA, Guyatt GH, Yepes-Nuñez JJ, Akl EA, Hazlewood G, Pardo-Hernandez H, Etxeandia-Ikobaltzeta I, Qaseem A, Williams JW Jr, Tugwell P, Flottorp S, Chang Y, Zhang Y, Mustafa RA, Rojas MX, Xie F, Schünemann HJ. 2019b.** GRADE guidelines: 20. Assessing the certainty of evidence in the importance of outcomes or values and preferences—inconsistency, imprecision, and other domains. *Journal of Clinical Epidemiology* 111:83–93 DOI [10.1016/j.jclinepi.2018.05.011](https://doi.org/10.1016/j.jclinepi.2018.05.011).
- Zhang Z, Li S, Wan B, Visentin P, Jiang Q, Dyck M, Li H, Shan G. 2016.** The influence of X-factor (trunk rotation) and experience on the quality of the badminton forehand smash. *Journal of Human Kinetics* 53(1):9–22 DOI [10.1515/hukin-2016-0006](https://doi.org/10.1515/hukin-2016-0006).